BEALE AIR FORCE BASE, PERIMETER ACQUISITION VEHICLE ENTRY PHASED-ARRAY WARNING SYSTEM
(Beale Air Force Base, PAVE PAWS)
End of Spencer Paul Road, north of Warren Shingle Road (14th Street)
Marysville vicinity
Yuba County
California

HAER CA-319
CA-319

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CA-319

PHOTOGRAPHS

WRITTEN HISTORICAL AND DESCRIPTIVE DATA

FIELD RECORDS

HISTORIC AMERICAN ENGINEERING RECORD
PACIFIC GREAT BASIN SUPPORT OFFICE
National Park Service
U.S. Department of the Interior
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San Francisco, CA 94103

HISTORIC AMERICAN ENGINEERING RECORD

BEALE AIR FORCE BASE, PERIMETER ACQUISITION VEHICLE ENTRY PHASED-ARRAY WARNING SYSTEM (Beale Air Force Base, PAVE PAWS)

HAER No. CA-319

Location: At the end of Spencer Paul Road, north of Warren Shingle Road (14th Street). Within the current boundaries of Beale Air Force Base, Yuba County, California.

USGS Smartville Quadrangle (7.5'), Universal Transverse Mercator Coordinates: 10 642677E 4332989N

Present Owner: United States Air Force

Present Occupant: Air Force Space Command

Present Use: The facility's primary mission is tracking sea-launched ballistic missiles (SLBMs) and intercontinental ballistic missiles (ICBMs). A secondary mission also exists, tracking space objects. A satellite communications station occupies Building 5771.

Significance: The Perimeter Acquisition Vehicle Entry Phased-Array Warning System (PAVE PAWS) at Beale Air Force Base is one of four large phased-array radars designed and built by Raytheon. PAVE PAWS was the first solid-state, phase-phase steered array radar operational in the world. The PAVE PAWS at Beale and that at Otis Air Force Base (today, Otis Air Force Station) on Cape Cod, Massachusetts, were the first two radars completed in the system. The original mission of PAVE PAWS was to monitor potential Soviet SLBM launches and to serve as early warning of an attack on the United States. A second pair of PAVE PAWS radars followed in the middle 1980s, sited in Texas and Georgia. The PAVE PAWS in Texas and Georgia are no longer operational. In 2002, Air Force Space Command initiated a major upgrade of the PAVE PAWS at Beale Air Force Base. The ballistic missile defense shield currently proposes to use PAVE PAWS as a platform for enhanced early warning radar, and to combine the system with missile interceptors.

I. PHYSICAL SETTING

Located approximately 60 miles north of Sacramento, Beale Air Force Base is spread across 22,944 acres in the southeastern corner of Yuba County. The installation is in the Sacramento Valley, nestled near the foothills of the Sierra Nevadas (Figure 1). The large communities nearest to Beale are Marysville and Yuba City. Marysville sits 10 miles west. Small towns in the immediate vicinity include Wheatland and Smartville. Air Force Space Command operates the PAVE PAWS radar today as a secure facility with an independent mission on base. Beale Air Force Base is configured a four distinct activity sites. The installation features a north-south runway along its western edge, a centered cantonment, and a family housing area in its southeastern corner. PAVE PAWS is located north of the family housing area at the end of Spencer Paul Road. Five entrances access Beale from the cardinal directions. Along the western perimeter of the base, the Main Gate on North Beale Road (to Marysville) is the closest entrance to the flight line and cantonment. Other points of entry are the Wheatland Gate at the southwestern corner, the Vassar Lake Gate at the southeastern corner, the Grass Valley Gate along the eastern edge, and the Doolittle Gate along the northern edge. The PAVE PAWS site is isolated within the boundaries of Beale. Microwave radiation safety zones exist surrounding the radar (Figures 2-3).

II. DESCRIPTION OF THE PAVE PAWS COMPLEX

The PAVE PAWS complex at Beale Air Force Base includes 12 buildings and structures, and occupies 60 acres in the northeastern corner of the installation. The primary, character-defining structures of the Beale PAVE PAWS are the radar (Building 5760) and its power plant (Building 5761). A passageway physically connects the two buildings. The remaining 10 buildings and structures of the PAVE PAWS complex are ancillary units constructed to support Buildings 5760 and 5761, or are later communications facilities added to the site.

Two fences surround the Beale PAVE PAWS, with surveillance and security devices augmenting the innermost unit. Fifteen hundred feet of security fence serves as the boundary of the secure installation. The fence outlines the radar (Building 5760), power plant (Building 5761), and satellite communications (SATCOM) terminal (Building 5771), along with all of the accompanying ancillary structures, in an approximate hexagon of unequal sides. This fence surrounds about four acres. An outer fence, described as a hazard fence, further surrounds the site, providing a 1000' buffer for the radiating array faces of the radar and circumscribing an additional 47 acres. The hazard fence is configured as 240 degrees of a circle, directly reflective of the radar coverage. The fencing for PAVE PAWS at Beale dates to 1979. In 1990, the Air Force installed a new security system around the radar site, adding and moving surveillance cameras, taut wire sensors, and infrared transmitter/receivers. The security system also includes an improved copper grounding grid at two distances along the inner side of the fence. By 1990, the Air Force had also increased the number of electromagnetic-pulse (EMP) filters at the Beale PAVE PAWS facility.

<u>Building 5760</u> (see the Architectural Data Form for HAER No. CA-319-A)

Building 5760 houses the radar and is alternately known as the Technical Equipment Building. Radar arrays are mounted on two facades of Building 5760, and have an arc-coverage of 240

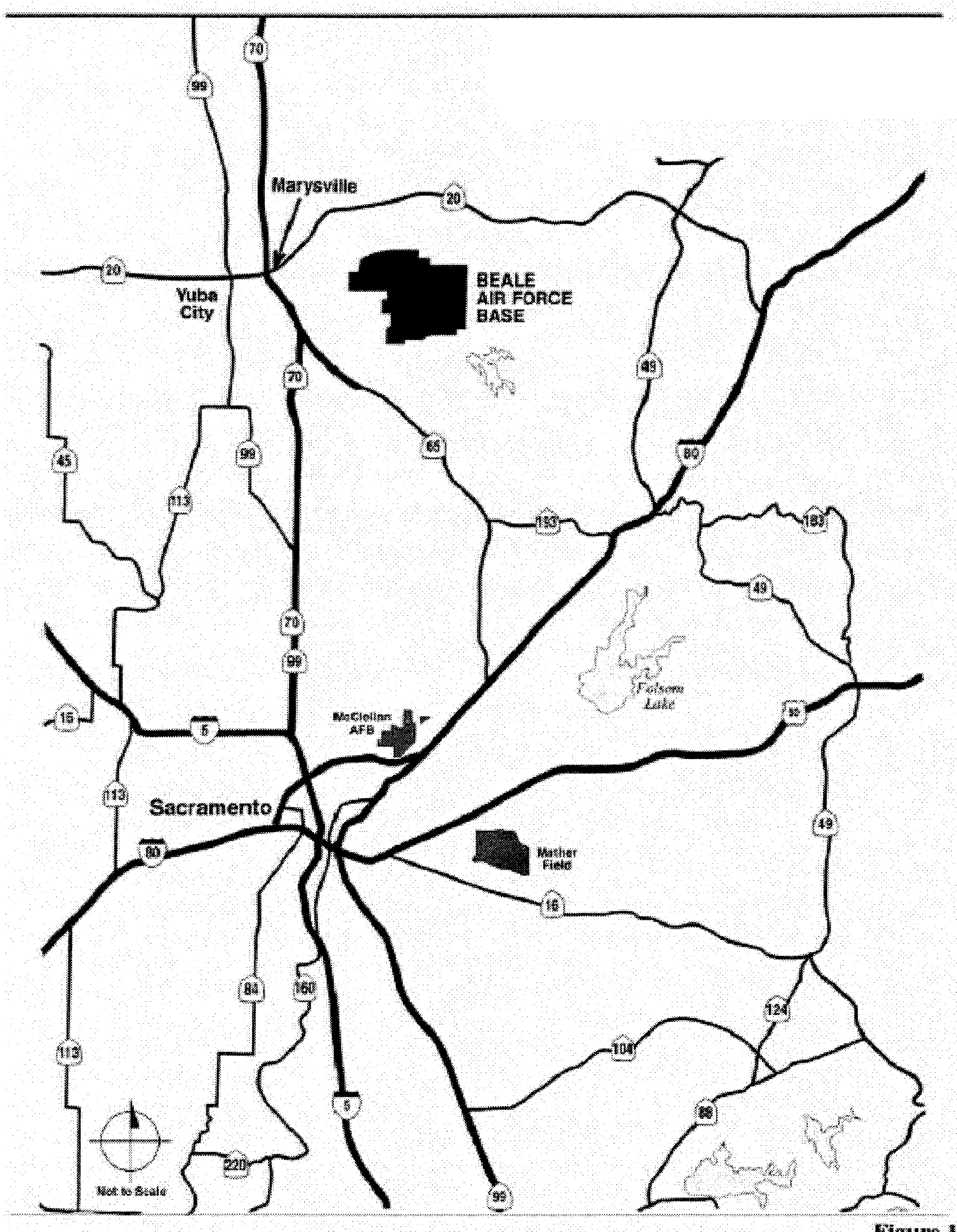

Figure 1
Vicinity Map
PAVE PAWS, Beale AFB, California

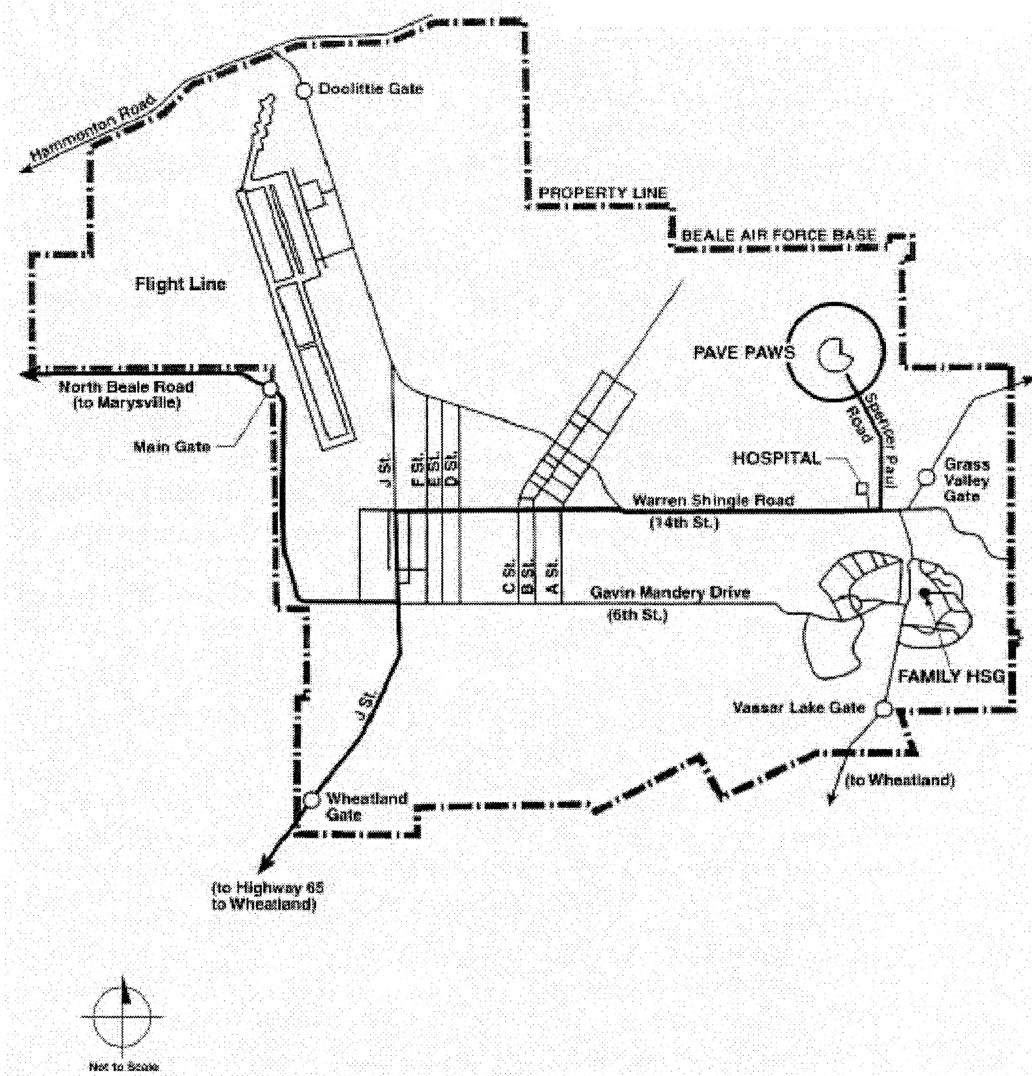

Figure 2
Location Map
PAVE PAWS, Beale AFB, California

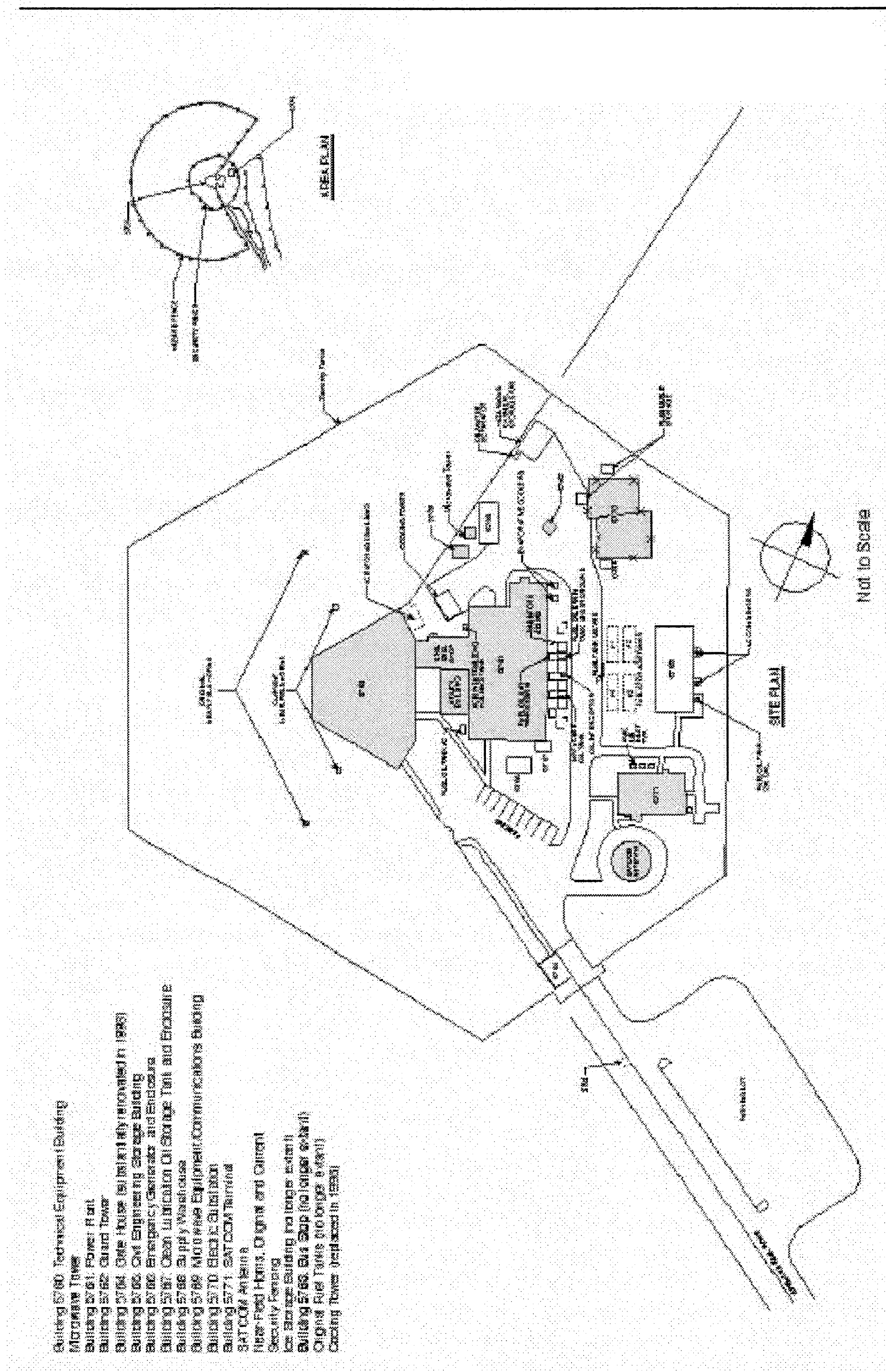

Figure 3
Building and Structure Identification Map

degrees. The radar facades each tilt back from the vertical at an angle of 20 degrees. The tilt of the radar arrays is a distinguishing feature of the PAVE PAWS radar. The interior of Building 5760 has five main floors, configured from the ground level upwards as maintenance and storage rooms, administrative and office space, computer and electronics operations facilities, a command post and communications center, and air conditioning equipment rooms. The Air Force has upgraded Building 5760 multiple times between 1979 and the present.

Several unnumbered ancillary structures augment Building 5760. A small, utility room is attached to Building 5760 along the passageway connecting Building 5760 and the power plant (Building 5761). A civil engineering shop and uninterrupted power source are interpreted as an expansion of the passageway undertaken during 1985. Two air conditioning units of the middle 1980s and a cooling unit of the late 1990s sit on the north side of Building 5760, replacing two original cooling towers and an ice storage structure. In 1990, the Air Force replaced the original near-field horns associated with Building 5760 with new near-field horns, physically locating these units 45' in front of each radar array. Miscellaneous hazardous and flammable storage tanks exist immediate to Building 5670, both above and below ground.

Building 5761 (see the Architectural Data Form for HAER No. CA-319-B)

Building 5761 houses diesel generators and operating equipment. Alternately known as the Power Plant, Building 5761 was designed as part of Building 5760. The Air Force separately numbered the structure post-construction. A passageway physically connects Building 5761 to Building 5760. In 1990-1991, the Air Force replaced the six original generators with new equipment.

Building 5762 (see the Architectural Data Form for HAER No. CA-319-C)

Building 5762 is alternately known as the Guard Tower and was an original component of the PAVE PAWS layout at Beale Air Force Base. When erected, Building 5762 doubled as a microwave tower, with an antenna mounted on its roof. The Air Force relocated Building 5762 within the PAVE PAWS compound in 1980.

Building 5763 (see the Architectural Data Form for HAER No. CA-319-D)

Building 5763 is alternately known as the Bus Shelter. The small structure is no longer standing.

Building 5764 (see the Architectural Data Form for HAER No. CA-319-E)

Building 5764 is alternately known as the Gate House, and functions as the security checkpoint for the PAVE PAWS compound. Today's Building 5764 replaces the original gate house on the same site. The Air Force demolished the original gate house in 1998.

Building 5765 (see the Architectural Data Form for HAER No. CA-319-F)

Alternately known as the Civil Engineering Storage Building, Building 5765 is a storage structure erected in the PAVE PAWS compound during the late 1980s.

Building 5766 (see the Architectural Data Form for HAER No. CA-319-G)

Building 5766 is alternately known as the Emergency Generator and Enclosure. Located adjacent to Building 5761 (the power plant), Building 5766 replaced an original emergency generator. Air Force personnel erected the current Building 5766 in 1985.

Building 5767 (see the Architectural Data Form for HAER No. CA-319-H)

Building 5767 is alternately known as the Clean Lubrication Oil Storage Tank and Enclosure. Air Force personnel collocated Building 5767 with Building 5766 during 1985-1990.

Building 5768 (see the Architectural Data Form for HAER No. CA-319-I)

Building 5768 is alternately known as the Supply Warehouse. The Air Force erected the warehouse at the PAVE PAWS site in 1987.

Building 5769 (see the Architectural Data Form for HAER No. CA-319-J)

Added to the PAVE PAWS compound in 1985, Building 5769 is alternately known as the Microwave Equipment Building. Building 5769 complements an unnumbered microwave tower placed on the original foundation of Building 5762 (the guard tower) in 1980.

Building 5770 (see the Architectural Data Form for HAER No. CA-319-K)

Building 5770 is alternately known as the Electric Substation and was an original component of the PAVE PAWS layout at Beale Air Force Base. The Air Force originally considered Building 5770 a free-standing component of Building 5760.

Building 5771 (see the Architectural Data Form for HAER No. CA-319-L)

Alternately known as the SATCOM Terminal, Building 5771 is the permanent operations structure for a secure, jam-resistant satellite communications antenna in the southeastern corner of the PAVE PAWS compound. The Air Force added the SATCOM facility to PAVE PAWS in 1984. In 1992, the Air Force augmented Building 5771 with a Military Strategic Tactical and Relay (MILSTAR) satellite system terminal.

III. CONSTRUCTION HISTORY FOR PAVE PAWS AT BEALE AIR FORCE BASE

The Air Force publicly announced that Beale Air Force Base would be the location for the second PAVE PAWS in mid-1975. Hiring the Stanford Research Institute, the Air Force completed an Environmental Impact Statement for the Beale PAVE PAWS between the initial announcement and March 1976. The Air Force awarded a $60 million contract to Raytheon for the design and construction of the Beale PAVE PAWS (7th Missile Warning Squadron 1980a, 3). Raytheon, Equipment Division, with United Engineers & Construction, completed drawings for the first and second PAVE PAWS, at Cape Cod Air Force Station in Massachusetts and Beale respectively, in January 1977. From March through September, the San Francisco firm of Tudor, Braccia Bentley employed the Raytheon and United Engineers & Construction drawings and materials to make a set of drawings explicitly for the Beale PAVE PAWS. Tudor Braccia Bentley served as the local construction architects and engineers for the job. Construction began on site in spring 1977.

Building activity for the Beale PAVE PAWS falls into several phases. Original construction occupied two-and-one-half years, between spring 1977 and November 1979. Adjustments at the site continued for about seven additional months. During December 1979, Strategic Air Command activated the 7th Missile Warning Squadron at the Beale PAVE PAWS. In mid-August 1980, the Air Force declared operational capability at the radar. In May 1983, Strategic Air Command transferred management of the PAVE PAWS to Space Command.

Although a number of local and regional architectural-engineering firms contributed to the upgrades and modifications at the Beale PAVE PAWS between 1980 and today, only a few are of significance in Cold War and architectural-engineering history. These include:

Raytheon Corporation and United Engineers & Construction, Boston,
as the original designers and components-makers for United States Army and Air Force large phased-array radars from ca.1965-2000;

Sverdrup & Parcel, St. Louis,
as the firm chosen to accurately render the as-builts for the Beale PAVE PAWS in 1985, using the Raytheon and United Engineers & Construction master drawings and a field check; and

Black & Veatch, Kansas City,
as the firm chosen to review and renovate the security and surveillance systems for the PAVE PAWS Upgrade in 1989-1991.

Today, United Engineers & Construction is a subsidiary of Raytheon, a company that continues in a leadership position for radar and weapons development. Sverdrup & Parcel completed the Beale PAVE PAWS as-builts simultaneously with the firm's work for the Air Force on Rail Garrison at Vandenberg Air Force Base in Southern California. Rail Garrison was a rail-mobile basing scheme for the MX Peacekeeper ICBM. Black & Veatch holds an uninterrupted position since 1946 as one of the most significant architectural-engineering firms known for Cold War military work in nuclear weapons storage, hardened structures, and surveillance.

Included within the original construction phase were:

1977-1979

the technical equipment building containing the radar (Building 5760),
the utility building (within Building 5760),
the power plant (Building 5761),
the cooling towers (immediately exterior to Building 5760), *today replaced*,
the guard tower (Building 5762),
the gate house (Building 5764), *today replaced*,
the electric substation (Building 5770),
the near-field horns, *today replaced*, with original horns abandoned intact,
four 40,000-gallon fuel tanks (unnumbered), *today replaced* with two 40,000-gallon tanks,

1979

the security / hazard fencing and surveillance devices (unnumbered), *today upgraded*,

1980

relocation of the guard tower (Building 5762), with no modification,
the microwave tower (adjacent to Building 5769), and
the bus stop shelter (Building 5763), *no longer extant*.

Between operational capability and 1998, the PAVE PAWS at Beale Air Force Base underwent four periods of renovation and upgrade. The improvements of 1982 completed construction at the site. Two major periods of renovations and upgrades followed: in 1984-1987 and 1989-1991. The improvements of 1997-1998 were substantially maintenance, and a working upgrade of operations. Modifications included:

1982

addition of first-floor computer facilities for Building 5760, *in place from 1982-1986*,
the first SATCOM antenna, with a communications van (unnumbered), *today replaced*,

1984-1987

an uninterrupted power source added to Building 5760,
a civil engineering shop added to Building 5760,
addition of civil engineering storage (Building 5765),
addition of the supply warehouse (Building 5768),
addition of the microwave equipment building (Building 5769),
a major addition to the electrical substation (Building 5770),
addition of a second power line into the installation,
addition of a permanent SATCOM terminal (Building 5771),
addition of the ice storage building and air conditioning units,
upgrading of security systems,

<u>1989-1992</u>

replacement of the computers, and other equipment, in Building 5760,
replacement of the diesel generators in Building 5761,
addition of new near-field horns,
addition of a concrete pad for the MILSTAR satellite system for Building 5771, with mechanical changes,
EMP checkout,
partial replacement and upgrading of the security and surveillance systems,

<u>1997-1998</u>

small maintenance projects,
replacement of the cooling towers,
demolition of the ice storage building,
replacement of the gate house (Building 5764), and
removal and partial replacement of the fuel tanks.

IV. DEFINITION OF THE LARGE PHASED-ARRAY RADAR

Defining physical characteristics for the Beale PAVE PAWS are generally those of the mature American large phased-array radar of the 1975-2001 period, although there are differences site to site across the PAVE PAWS and upgraded Ballistic Missile Early Warning System (BMEWS) radars.

(1) <u>Location</u>: The location of the PAVE PAWS in a remote area of Beale Air Force Base, as well as its hilltop site, is integral to the safe working of the radar on an Air Force base near populated areas. An immediate, secured buffer of four acres surrounds the radar, with an additional 46 acres forming a secondary buffer to provide a zone 1000' in radius in front of the two actively radiating array faces of the technical equipment building (100th Air Refueling Wing 1977, 9). The site elevation of 372' above sea level, in combination with the lower parameter of three degrees in vertical projection, is the key design feature that keeps the emitted radiation always above 100' (National Research Council 1979, 4).

(2) <u>Size</u>: All American and former Soviet missile early warning phased-array radars are very large. Those in the United States that comprise the PAVE PAWS and upgraded BMEWS networks are a little over 100' in height and width, with a trapezoidal footprint and a truncated pyramidal form. The shape of most large phased-array radars accommodates a lessening of radar blocking and impedance caused through irregular forms, and nominally minimizes blast damage in the case of reinforced concrete structures. In large phased-array radars, the "electrical shape" is independent of the shape of its housing infrastructure (Constant 1972, 193-197). To achieve a maximum coverage in azimuth, such as 240 degrees at the four PAVE PAWS sites and 240 or 360 degrees at the

three upgraded BMEWS sites, American large phased-array radars built post-1977 have had two to three active radar faces.

(3) Angle of the radar face: A 20-degree setback characterizes the faces of the PAVE PAWS and the PAVE PAWS-type large phased-array radars of the upgraded BMEWS. To date, there have been three published setback angles for large phased-array radars, inclusive of those radars in the United States and in the former Soviet Union. Nominally, the 45-degree (high boresight) angle is always discussed in available literature as the appropriate angle for spacetracking, while the 20-degree (low boresight) angle is noted as that appropriate for monitoring objects coming in over the horizon in near-earth atmosphere. A 30-degree setback characterized the Missile Site Radar erected in the Kwajalein Atoll during the early 1960s, and possibly the Perimeter Acquisition Radar in North Dakota. ICBMs travel at an optimal trajectory low over the curvature of the earth at about 20 degrees above horizontal. The 20-degree setback allows for scanning in elevation from three to 85 degrees above horizontal. Scanning in either elevation or azimuth has an effective parameter of 60 degrees off boresight (antenna center).

(3) Materials: Large phased-array radars built for an early-warning mission have evolved from a dual path of thick-walled, reinforced concrete structures and steel-frame structures, the latter sheathed in insulated-aluminum panels, to a single path of steel-frame, insulated-aluminum panel structures. The first American large phased-array radars were of both types. Those built for the antiballistic missile (ABM) defense program were hardened, reinforced concrete structures, both in the Kwajalein Atoll and in North Dakota, while that at Eglin Air Force Base was a steel, aluminum-paneled structure. Theoretically, the reinforced concrete choice protected against nuclear blast overpressures, while the steel-frame choice did not. However, engineers soon realized that the reinforced concrete structure would not survive a direct or near-direct hit, as it was either fully or partially aboveground. It was also evident almost immediately that the selection of a thick-walled, reinforced concrete structure to house the radar greatly increased what were already enormous costs (Allen 1962, 77-78; Constant 1972, 220). The steel-frame, aluminum-paneled choice lowered the costs and construction time, concentrating the issues of hardening on EMP, a nuclear effect discovered in 1958, rather than on blast. EMP especially damaged delicate electronics, such as the microprocessors in the computers of the large phased-array radar.

(4) Position-fixing capability: A distinction of the PAVE PAWS is its ability to detect and track in three dimensions. Military air defense radars today are typically of two-dimensional and three-dimensional capability (Cole 1992, 280; Winkler 1997, 84). The PAVE PAWS employs phase-phase steered arrays. Phase steering allows the

radar to scan in two dimensions. The PAVE PAWS accomplishes time-delay steering, through the incorporation of subarrays on each face of the radar. Time-delay steering eliminates pulse width dispersion, and allows the transmitted radar pulses that leave the top and bottom of the radar antenna array to arrive at their target at the same time. In turn, radar returns reflected off the target permit the third-dimension calculation (Brookner 1997, 3-4). The planned "target" was the warhead of an ICBM or SLBM, also known as a reentry vehicle (RV).

As noted by Dr. Brookner in his chapter on large phased-array radars in *Nuclear Arms Technologies in the 1990s* for the American Physics Institute: "Large phased-array radars…can be used to determine the number of RVs being deployed, the type of targeting of the RVs (the same or different targets), the shape of the deployed objects, and possibly the weight and yields of the deployed RVs." Dr. Brookner comments that, dependent on what is being observed where and when, assisted by what upgrading, it is now possible to refine assessments of incoming ballistic missiles by their distinctions as multiple reentry vehicles, multiple independently-targeted reentry vehicles, or maneuvering RVs. The radars can also distinguish decoys under the right circumstances (Brookner 1988a, 165-167).

(5) Thinned arrays: Raytheon designed PAVE PAWS based on a thinned array of antenna elements. Array thinning achieved several military goals for the first mature American large phased-array radars. By dead-heading a number of the radiating elements of a large phased-array radar, engineers reduced the overall array cost, while simultaneously increasing the angle accuracy. The cost of a phased array is approximately proportional to its number of elements (primarily tied to the cost of the phase shifters). A thinned array also produces a narrower beam width, which in turn creates better tracking performance. In counterpoint, search performance is poorer, with more time needed to search a certain volume of space. Use of thinning further creates a reduced antenna gain and far out side lobes. Arrays can be thinned either by equal spacing between elements, or unequal spacing. If configured with unequal spacing, an array can contain fewer elements, as compared with an equally spaced array, to achieve comparable beam width. Unequal spacing also "smears" the undesirable sidelobes produced. PAVE PAWS and the upgraded BMEWS are long-range detection and tracking radars, as originally built and currently used. Air Force Space Command can expand them for better tasking in a search mode. From the first, engineers understood that array thinning did not interfere

with future systems expansions (Brookner 1991, 2-27, 2-37; Skolnik 1962, 315).

(6) Frequency band: Early warning radars have evolved from characteristic frequencies in the very high frequency (VHF) range, to ones in the low ultra high frequency (UHF) range, to uniform UHF ranges of 400-500 megahertz (MHz). PAVE PAWS operates in the 450 MHz range.

During the 1940s, radar advanced rapidly with a general increase in used frequencies from high frequency (HF) to VHF to UHF to microwave, up to the K-band. With the 1950s, there was a distinct return to lower frequencies, in order to achieve long-range detection and tracking of first aircraft and then missiles. The use of VHF frequencies required large antennas for this purpose (Skolnik 1985, 185).

As the 1960s opened, a second more subtle transition from VHF to a distinct range of UHF held true for both the American and Soviet early warning radars. The jump to large phased-array radars later in the decade was also accompanied by the shift from the VHF to UHF range of approximately 425-450 MHz. The shift was reflective of an increased understanding of the needs for early warning. The BMEWS fixed-fence radar, the AN/FPS-50, also operated in the 425 MHz range. Exceptions to the 425-450 MHz range for large phased-array radars were ABM and intelligence radars, all of which operated above the 1000 MHz range (White 1984, 1108). Frequency choice for the early warning radar, generally, is partially determined by the large size of these radars, which do not lend themselves to high UHF and above due to their need for longer wavelengths to accommodate long-range search (Gross, Hall and Barton 1974, 6).

Radars operating at UHF rather than VHF are also less susceptible to the phenomenon of blackout, a radar blinding condition. The fireball of a nuclear detonation in the atmosphere ionizes the air, which causes blackout. The resultant ionized plasma gas cloud bends and absorbs electromagnetic waves, particularly ones of low frequency. If the intent is to track inbound ICBMs, or to intercept ICBMs above the upper atmosphere, blackout poses a substantial problem for large phased-array radars. Blackout could occur either through a deliberate strategic enemy nuclear detonation at high altitude, or by defensive nuclear explosions (Constant 1972, 32).

Finally the VHF and UHF ranges partially reflect the development of modern American society, particularly urban society. The 420-450 MHz range is considered the military radar band. The VHF band below this, as well as the UHF band above, include television, and thus would have enormous potential for interference (Burress 1998).

(7) Continuous simplification of radar hardware:

In the United States, large phased-array radars have evolved toward consistently simpler radar hardware, affecting interior and exterior appearance, mean time between failures, and operation costs.

The first generation of large phased-array radars used klystrons, tetrodes, and traveling wave tubes, rather than solid-state, transmit-receive modules. These radars included ABM, tracking, early warning, and intelligence types, from the Missile Site Radar to Cobra Dane. Klystrons are early technology, operationally dating to the late 1940s. Engineers tried tetrodes for a large phased-array radar only in the AN/FPS-85 at Eglin during the 1960s. Traveling wave tubes were the primary alternate choice to transmit-receive modules. The traveling wave tube requires much more hardware on the backside of the array and is prone to constant maintenance. Items inclusive of subarray divider units, three-inch diameter coaxial cabling, high-voltage modulators and power supplies support the traveling wave tube technology and are entirely absent from solid-state transmit-receive technology (Brookner 1988b, 29-31). The transmit-receive modules, first introduced for large phased-array radars with the Cape Cod and Beale PAVE PAWS, were the single greatest feature change for overall system cost reduction at the time Raytheon introduced them (Skolnik 1990, 7.2). They consist of two nested boxes containing transmitter and receiver components and circuitry, additionally incorporating the transmit-receive switching, a two-stage, low-noise amplifier, limiter, a four-bit phase-shifter, and logic control (to handle the phase-shifting row-and-column commands) (Skolnik 1990, 5.25). The latter eliminates the need for individual module control wiring. A cold plate sits directly beneath the transmit-receive module, through which operators cycle liquid coolant. The solid-state transmit-receive modules also have increased the running efficiency of the large phased-array radar, with modules able to operate 150,000 to 200,000 hours before failure. PAVE PAWS can run for one-and-one-half to two years without replacement of its transmit-receive modules, a precedent for large phased-array modules that was new with the Cape Cod and Beale facilities. Such run time, of course, helps to make large phased-array radars effective 24-hour-a-day, 365-day-a-year installations (Laighton 1988, 279-283).

A second distinct change due to the simplification of the hardware for the large phased-array radar affected the overall design of the radar's infrastructure. The first American large phased-array radar, that at Eglin Air Force Base, has separate radar faces placed side by side for transmitting and receiving, foreshadowing the configuration of two fully separated transmitting and receiving structures for the large phased-array radars of the Soviet Union. Beginning with ABM radars in the 1960s, and codified with the Cobra Dane intelligence radar in the early 1970s, American large phased-array radars have combined transmitting and receiving within single radar faces, handling the challenges through the development of radar hardware and its accompanying computerized control.

Further simplifying the transmitting and receiving functions of large phased-array radars is the system's use of a *confined*, also known in one of its subcategories as a *corporate*, feed. This type of system uses waveguides, coaxial cable or some type of closed transmission path to provide the antenna with radiating power. In many radars the feed mechanism is of space or optical type, using a horn, or cluster of horns, to directly radiate the antenna. Corporate feed allows for the use of fewer transmitters than dipole elements, making it possible to have dummy elements in place for future expansion. The complexity of a large phased-array radar, or any array, is partially proportional to the number of its individual antennas, here dipole elements (Allen 1962, 62; Constant 1972, 191, 201; Stark 1974, 1692-1698).

Simplifying the hardware for the large phased-array radar reduces its building blocks, and is directly interpreted as important for costs (Allen 1962, 78). Reuse of parts, shipping unneeded parts from one large phased-array radar to another, is also key. The Air Force returned unneeded heaters for the dipoles at the Beale PAVE PAWS to the radar at Cape Cod, for example, to be used as spares (Burress 1998). The upgrade of the BMEWS at Clear Air Force Station in Alaska as a PAVE PAWS-type large phased-array radar kept costs in line by disassembling the radar faces of the Eldorado PAVE PAWS in Texas and shipping the parts to Alaska for creation of the radar there (Hall 1998).

(8) Planned upgrading: Engineers designed American large phased-array radars from the beginning to be upgraded, to allow for a probable future increase in transmitted power and system sensitivity.

Planned system increase directly affects the configuration of the individual dipole elements on the face(s) of the large phased-array radar. American large phased-array radars all illustrate the concept of array thinning, whereby active elements (those connected via traveling wave tubes or transmit-receive modules to the power source) are denser in the center of the face (boresight) and considerably thinned through the placement of dummy elements (those not connected to traveling wave tubes or transmit-receive modules and a power source) as one moves out from boresight. Making dummy elements into active ones is planned as factoring exercises, with discrete groups of elements needed for each new plateau of transmitted power and receiver sensitivity. Power and sensitivity are discussed as decibel levels, effectively referencing the receiver power level, and translate to an enhanced ability to see ever smaller objects near earth and at greater distances (Brookner 1988b, 28; Hall 1998).

The PAVE PAWS large phased-array radars at Cape Cod and Beale, as originally built, are considered "0-decibel systems," the base level for the system, while Raytheon designed the third PAVE PAWS at Robins as a "6-to-10 decibel system." At 0 decibels, PAVE PAWS could see objects 10 meters square at a maximum range, objects also described in written literature and verbally as "the size of a Volkswagen bug" (Emich 1998; Hall 1998). To achieve a 6-decibel system, the number of active elements is doubled on each face of the radar to 3,584; to achieve a 10-decibel system, all of the dipole elements for PAVE PAWS (5,376) are activated (Burress 1998). At the time of construction for the Robins and Eldorado PAVE PAWS, the original two PAVE PAWS at Cape Cod and Beale received upgrades to an "improved 0-decibel system." The Air Force planned for the Robins radar to start up at 10 decibels, as well as intending that Beale's PAVE PAWS would become a 6-decibel facility (Hall 1998).

In addition to providing for a larger number of individual dipole failures without causing serious system degradation, the choice of dipoles as the individual radiating elements also lends itself to the planned longer term upgrading for large phased-array radars and to a quick response for immediate upgrading should that be needed. The parts are relatively simple, are manufactured in multiples, and are built into the original radar faces as active and dummy elements only requiring power connection. Dipole elements also work well in the frequency range characteristic of the early-warning, large phased-array radar, and allow for a fast rise to peak power. The ability to increase radiated power, as distinct from the creation of a large receiving array, was understood from the earliest years as a necessity for operation in an enemy jamming environment (Allen 1962, 77-78; Constant 1972, 185).

(9) Networks and system redundancy:

American and former Soviet large phased-array radars, in their post-1977 configuration, are networks with overlapping radar coverage and system redundancy for each nation, with coverage and redundancy required to offset the contingencies of nuclear warfare.

The mature large phased-array radar networks of the two Cold War enemies went into place over a 25-year period, beginning in 1976. The American radars primarily represent the second phase of technology for the large phased-array radar. They total seven, including the four PAVE PAWS and the three upgraded BMEWS. Three additional first-generation, large phased-array radars, those at Eglin (1962-1969), the converted Perimeter Acquisition Radar from the Safeguard ABM system in North Dakota (1969-1975), and Cobra Dane in the Aleutians (1973-1977), supplement the American network. The parallel network of large phased-array radars in the former Soviet Union, known as Hen Roost, was also a 10-radar network, backed by the transitional early-warning, 11-radar network known as Hen House. The former Soviet, large phased-array radars are now sited in Russia and individual countries formerly within the boundaries of the Soviet Union.

Each of these networks blankets their respective land masses in a comprehensive radar fence. Radars are generally sited at the peripheries of the North American continent and the former Soviet Eurasia, with individual radars covering a horizontal arc of 120, 240, and 360 degrees, dependent upon design as a single-, double-, or triple-faced large phased-array radar. Coverage overlap, as well as redundancy, is designed to handle the contingencies of individual loss due to direct hits and temporary blinding due to blackout.

(10) A multipurpose system: Large phased-array radars are evocative of a mature weapons system whereby the incorporated technologies tend to make the system multipurpose, with an unclear distinction between a purely offensive and defensive system (Jasani 1987, 5).

Both American and former Soviet large phased-array radars can perform as battle management radars, thus providing more than early warning. In this regard, the evolution of the early-warning, large phased-array radar directly from the radars of the Safeguard ABM system is not coincidental. The large phased-array radar is potentially both a tactical and strategic military asset.

V. THE TECHNOLOGY OF PHASE-PHASE STEERED ARRAYS

As stated by Merrill I. Skolnik in his pivotal radar text of 1962 *Introduction to Radar Systems*: "Radar is an electronic device for the detection and location of objects." Radar transmitters emit electromagnetic radiation, while radar receivers detect energy reflected off the surface of encountered objects. Earliest experimentation toward radar dates to the late 19th century, with both the German and American Navies making significant strides during the 1920s and 1930s. By the late 1930s, the United States Army Signal Corps also tested radar devices. As of 1939, the Army had its first long-range detection radar, the AN/SCR-270. Six of these radars were operational in Hawaii during late 1941, detecting the attack on Pearl Harbor. Development of a microwave radar, using a magnetron developed on British models, became the mission of the Radiation Laboratory at the Massachusetts Institute of Technology in November 1940. The first full-fledged radars of World War II focused on the detection of hostile approaching aircraft and on the management of antiaircraft weapons. The term radar illustrates this origin, and is derived from radio detection and ranging. Following the war, radar development slowed briefly. Long-range surveillance radars soon included the AN/CPS-6B, AN/FPS-3, and AN/FPS-6. By the early 1950s, new developments pointed toward the PAVE PAWS technology. The first of these was the high-power klystron amplifier (engineered for the linear accelerator at Stanford University and adapted for radar). Klystrons have the capability of greater power output than do magnetrons. They are also more stable, and as a result encouraged the design of better moving-target-indication radars. Another important improvement occurred in the engineering of receivers. Crystal-mixer technology and low-noise traveling wave tubes improved the sensitivity of microwave receivers, as noted by Skolnik, by an order of magnitude. Yet another advance of the later 1950s was the closer integration of radar to weapons systems, possible due to advancements in computer technology. The foremost example of this progress was in the realm of guided missiles and air defense systems of the late 1950s and early 1960s. Development of intermediate range ballistic missiles and ICBMs at the close of the 1950s, as well as the first satellite launchings, directly led to the development of radars with very high-power transmitters and large antennas (Skolnik 1962, 1-19).

PAVE PAWS is a sophisticated radar, one that is within the general family of what are known as electronic scanning radar systems. Raytheon phased-array radar expert Peter J. Kahrilas defines electronic scanning as "a method of positioning an electromagnetic beam in space by electronic means with the antenna aperture remaining fixed and no mechanical mechanism involved in the scanning process" (Brookner 1991, 1-2). Basic modern military needs are well aligned with large phased-array radars. The radars offer: (1) increased range coverage, (2) increased resolution, and (3) shorter reaction time. This type of radar also achieves the goal of a single, integrated system. Electronic scanning radar systems generally, and large phased-array radars in particular,

- can operate simultaneously in multiple modes such as search, multi-target acquisition, multi-target track, multi-missile guidance, automatic reacquisition of lost targets, kill evaluation, and passive detection;
- allow large power-aperture products;
- achieve high data rates;
- are suitable for computer control and data processing (contributing to fast reaction time);
- are electronically stabilized, with space coordinates referenced to a fixed element rather than a moving platform;
- are very reliable due to component redundancy, making catastrophic failure improbable;
- have minimal downtime for repairs, with computer-controlled diagnostic routines run as self tests and with relatively few different types of necessary spare parts; and,
- have substantial "growth potential."

With respect to the last item, PAVE PAWS-type radars can add transmit-receive modules at a later date to support an increased data rate and to achieve faster reaction time. Disadvantages of the PAVE PAWS-type radar are relatively few, focused on its complex design, its high cost and lengthy construction time, and the continuing need for the development of ever-better components. As Theodore C. Cheston of the Naval Research Laboratory wrote in 1990: "Complete flexibility is possible...The functions may be programmed adaptively to the limit of one's capability to exercise effective automatic management and control" (Skolnik 1990, 7.1).

Evolution of Phased-Array Radar Components

Hardware

Phased-array radars have a basic number of critical components, with aspects of their design, engineering, and function summarized in a generalized manner above. The construction cost of large phased-array radars is very high, with maintenance costs also an important factor. As early as 1962, radar engineers realized that a reduction of the hardware associated with an array radar was a major goal, best achieved through a continuous standardization of hardware and a building-block approach (Allen 1962, 78). PAVE PAWS is particularly evocative of a maturation of these concepts. Specific key hardware of PAVE PAWS includes:

- the radiating antennas (elements)—typically defined as the combination of a radiator and a phase shifter;

The radiating antennas of the PAVE PAWS are dipoles. In contrast, at the time the Air Force built PAVE PAWS, the alternate choices for configuring the aperture of a phased-array radar were waveguide horns and traveling wave radiators relying on polyrods. Radars operating at low frequencies more often used dipole antennas. Those configured with waveguides offered the capability for a highly accurate and refined tracking analysis. The use of dipoles pointed to the primary search mission for a radar like PAVE PAWS (Brookner 1991, 4-1 – 4-3).

The dipole radiating elements of PAVE PAWS are 8" high, described as "crossed-dipole" or "bent-cross dipole" elements in technical radar literature. The downward bent alters electromagnetic interactions between adjacent elements. At certain steering angles, such electromagnetic interaction would prohibit microwave energy from radiating outward from the radar face. Without the downward bent, the phenomenon of "radar blindness" would occur at such steering angles. An ancillary feature to the dipole antennas are the metal stubs set between them. The stubs help to produce a circularly polarized transmission beam. This type of beam maximizes the sensitivity of the PAVE PAWS radar (Brookner 1988a, 176).

While large phased-array radars can use separate antennas for transmitting and receiving (such as in the large phased-array radar at Eglin), the PAVE PAWS radars combine the two functions on each of the radar faces. Equipment installed behind the face of the array, connected to the dipole antennas, includes:

- a driver (in the case of PAVE PAWS, a predriver and subarray drivers);
- phase shifters;
- power amplifiers;
- low-noise receivers;
- beamformers;
- power generators; and,
- power supply.

For PAVE PAWS, the transmit-receive module is especially important hardware. The solid-state transmit-receive module contains a phase shifter, transmitter, and receiver for each connected dipole element. On transmit, the exciter signal passes through a phase sifter in the transmit-receive module, and then feeds into the four bipolar silicon, 100-watt UHF transistors hooked in parallel in the transmitter. On receive, the signal from the dipole element passes through a low-noise receiver, to the same phase sifter used during transmitting, and thence to a beamformer. Thus, the phase sifter, power amplifier, and receiver hardware are all combined in one standardized unit, the transmit-receive module (Brookner 1988a, 173). PAVE PAWS is an active phased-array radar, as distinguished from a passive phased-array radar. In active phased-array radars, the power amplification occurs after phase steering (see below), rather than before such steering (Brookner 1997, 4).

In PAVE PAWS, each of the radar's two arrays is divided into 56 subarrays, with each subarray consisting of 32 active transmit-receive modules that fed an equivalent number of radiating elements. This translates into the 1,792 active elements of each PAVE PAWS radar face, as designed and built. An upgrading to a higher decibel level through the adding of more transmit-receive modules, connected to existing dummy elements, would also create additional subarrays (see below). Engineers mounted subarray drivers on the girders on the backside of each array face. Subarray drivers are identical to transmit-receive modules, except that they do not use their receiver portion. Predrivers are also transmit-receive modules, adapted without activation of their receiver component. Predrivers drive the subarray drivers. Power supply units for the transmit-receive modules functioning as predrivers, subarray drivers, and array element modules stand as independent units along the corridors of each floor behind the two radar faces. Power generators, in the power plant at the rear of the radar (Building 5761 for the PAVE PAWS at Beale Air Force Base), feed the predrivers, in turn drawing upon the electrical power delivered to the radar via an electric substation on the premises. Under normal circumstances, a power line from local utilities suppliers brought power to the installation. As a preparation for unusual conditions, such as a war, PAVE PAWS also included large underground fuel tanks for emergency power supply. The combined system of drivers and element modules found in PAVE PAWS, all using transmit-receiver modules as their basic building block, represented a major reduction and standardization in the hardware needed for the American large phased-array radar—an achievement noted among the engineering community (Brookner 1984, 3 and Brookner 1988a, 176).

Final hardware required in a PAVE PAWS radar includes its computers and radar equipment. To achieve a maximum efficiency in both cost and operation across the system of PAVE PAWS radars, the sophisticated computers are "off-the-shelf," rather than specifically designed for the radar. Computer standardization, like that of all components of PAVE PAWS, facilitates use of interchangeable parts, with the reuse of the hardware from the PAVE PAWS at Eldorado, Texas, for the upgraded BMEWS radar at Clear, Alaska, a perfect example. Programming software placed on the machines is what makes the computers specific to PAVE PAWS. This approach has been in place for American large phased-array radars since Cobra Dane (Brookner 1988a, 169). As an example of one important task, computers for PAVE PAWS perform the steering computations. The computer can compensate for phase errors caused by the individual microwave components, as well as for the operating environment and the physical placement of the individual radiating elements in the thinned arrays. Operating environment, as a further example, can include temperature differentials across the two arrays, which without computer compensation would cause phase errors. The nearly 2,000 elements of each PAVE PAWS array require many, many calculations for beam steering (Skolnik 1990, 7.21).

Software

From the outset, the software programs of the computers used for all multi-function radars, including PAVE PAWS, were of primary importance. A single computer frequently housed both radar control functions and user processing functions. In a lecture given in the middle 1970s, Dr. Walter Weinstock of RCA in Moorestown, New Jersey, cited the large phased-array radar at Eglin Air Force Base—a forerunner for PAVE PAWS, as just such a multi-function radar. Dr. Weinstock further noted that the control computer "determines the angular position of the beam, the time of transmission, the frequency, the waveform and pulse period to be used, the appropriate detection threshold, and the appropriate support information." A multi-function radar features four basic functional processes: search and detect, transition to tracking, track maintenance, and user services. PAVE PAWS is a multi-function radar designed to handle each of these processes, but is focused on search and detect. By definition, a multi-function system's taskings are not all of equivalent priority, which dictates that a lower priority function can be held in abeyance while that of higher priority is dominant. Some taskings also demand a timed interval looping. Among tasks which the computer must handle well, in order for a radar like PAVE PAWS to accomplish its mission, are excluding extraneous data, avoiding redundant detections, controlling multiple detections, and preventing false alarms. The software of the multi-function computers literally "provides the mechanization for fulfilling these requirements" (Brookner 1991, 11-1 – 11-7, 12-1).

Working Principles

PAVE PAWS is a phase-phase steered array radar. Engineers have set phase shifters incrementally across the vertical direction (for scanning in elevation) and across the horizontal direction (for scanning in azimuth). The term "phase-phase array" refers to electronic phase-lag steering in both elevation and azimuth.

Phase Shifting

Phase shifters tilt the microwave beam without mechanically rotating the radar array. Radar signals from the elements diverging from boresight travel different distances to their target. Without phase shifting, the signals interfere with each other and weaken all but a narrow beam at boresight. In basic terms, if elements radiate in phase, the radar sees straight ahead at boresight. Using phase shifters, engineers cause the electronic radar signal to lag a fraction of a wavelength from one adjacent element to another in increments based on multiples of theta. This process creates the required sum signal (that detects targets) to the side of boresight, in the direction of the increasing phase delay. The radar beam remains narrow (typically called a pencil beam), with its angle reflecting "the magnitude of the phase shift, the size of the array and the wavelength of the signals" (Brookner 1985, 96). Computer programming allows the calculations needed for phase shifting, also accommodating very fast movement for scanning at different angles and in different sectors. The capabilities of the computer used for PAVE PAWS can redirect the radar beam from potential target to target, in microseconds. The effective scanning area of an array does have defining parameters, however, largely determined by steering angle. About 60 degrees from boresight an array rapidly loses its sensitivity to returning radar echoes, and thus becomes ineffective for search, detection, and tracking. This fundamental limitation underlies the 120-degree scanning capability of PAVE PAWS in azimuth, per array, as well as its 85-to-3-degree scanning capability in elevation.

Pulse Coding and Pulse Compression

Phased-array radars can transmit at various lengths of energy pulse, refined for the mission of the equipment. For PAVE PAWS, the radar transmits its beams both as long and short pulses of energy. Longer pulses serve for detection and tracking, but have significant limitations. Four major rationales exist for the selection of a brief pulse: (1) to distinguish objects moving in close formation, (2) to gauge the size and identity of the target, (3) to accurately determine the distance of an incoming object, and, (4) to lessen the radar signal's susceptibility to extraneous clutter from precipitation conditions and from ground sources. The objects in close formation that concern the men and women monitoring the consoles in the PAVE PAWS command post are multiple independently-targeted reentry vehicles. By reflecting a radar echo off the fore and aft ends of the warhead through an extremely short pulse, it is possible to determine some of its specifications, and hence its likely identity. The most immediate needs of PAVE PAWS monitors, however, are to refine the distance parameters and to clarify the incoming information.

Short radar pulses present particular challenges. When transmitting a short pulse at a large angle to boresight, the pulse becomes distorted as the energy moves through space toward its target. The pulse stretches in both time and space. The briefer the transmitted pulse, the greater the potential for distortion. For example, returning echoes from a warhead's fore and aft (or objects in close formation) may merge together, and no longer allow an accurate reading of the information the signals represent. To prevent this situation, engineers typically seek to preserve the original shape of a brief energy pulse. Programmers achieve this through a time-delay steering of subarrays so that the signal arrives together rather than distorted by its travel. To send the very short pulse required, the radar must have a high peak transmission power. PAVE PAWS does not have this kind of power. Solid-state circuitry, such as defines PAVE PAWS, offers both efficiency and cost advantages—but is traded for much lower peak power than that available in a radar using traveling wave tubes. To offset this disadvantage, engineers for PAVE PAWS have developed the techniques of pulse coding and pulse compression. As stated by Dr. Brookner, these techniques "enable a radar to simulate a brief, high-powered pulse by emitting less powerful signals for a longer period of time." To achieve this kind of short pulse, the radar begins with a short pulse (such as the five-nanosecond pulse often cited for transmission at Cobra Dane), passing it through delay lines to lengthen it, then amplifying the pulse and transmitting it as a longer signal. On return, a compressor network delays the reflection inversely, to create an undistorted five-nanosecond radar echo. The compressed echo allows segregation of information merged with longer pulses, for example. Again, Dr. Brookner summarizes the advantages of these techniques for detection and search radars such as PAVE PAWS, also pointing to one way in which these radars can function in a battle management mode: "Pulse coding and pulse compression enable such radars to reconcile range and resolution with low power" (Brookner 1985, 101).

VI. HISTORICAL CONTEXT – BEALE AIR FORCE BASE

The Installation

[Unless otherwise noted, the author has summarized information presented in *From the Stone Age to the Space Age: A History of Beale AFB* for the section below (Cross 1997).]

The United States Army established the first military installation on a portion of the current Beale Air Force Base site in 1942. Activated in October that year, Camp Beale opened as a training base for the 13th Armored Division through 1943. During World War II, Camp Beale grew to a size of over 86,000 acres with 60,000 men and women, supporting an airfield as well as a large cantonment. After the war ended, the War Department declared the installation surplus in May 1947. The National Guard used parts of the former Camp Beale for continued training, while the War Assets Administration sold off many of the installation's buildings. The United States Air Force, a newly established arm of the services which had evolved directly out the Army Air Forces of World War II, first assumed control of Camp Beale through Air Training Command as a bombing range attached to Mather Air Force Base's Bombardier-Navigation School in Sacramento.

The 1950s were a decade of change for Beale. In early 1951, the host command for the Beale Bombing and Gunnery Range shifted from Air Training Command to Continental Air Command. The Air Force changed the status of the installation from that of a bombing range to an independent Air Force base late in the year. Before mid-decade, Beale Air Force Base planned only a few high-priority Cold War missions. Beale shifted host commands to Strategic Air Command in late 1956. In early 1957, engineers undertook the construction of a new 12,000-foot runway to accommodate the arrival of the B-52 bomber and its accompanying KC-135 tanker. Beale was one of 65 Air Force installations supporting Strategic Air Command alert. In 1959, Air Defense Command added an important tenant mission at the base, that of a Semi-Automatic Ground Environment (SAGE) Direction Center for the San Francisco Air Defense Sector, operational from 1959 to 1963.

During the early 1960s, many Cold War missions at Beale went through a rapid transition, reflecting the new role of the ICBM in military planning. In 1961, the Air Force constructed three Titan I launch complexes surrounding Beale at Lincoln, Chico and Sutter Buttes. Strategic Air Command declared the complexes operational in early 1962, maintaining them on alert status until their phase-out in early 1965. In the middle 1960s, Strategic Air Command shifted its mission at Beale to strategic reconnaissance, deploying the SR-71 Blackbird to the base and renovating the vacant SAGE building for a new role associated with the spy mission. The SR-71 flew at above 80,000 feet, capable of speeds beyond Mach 3. Strategic Air Command maintained the SR-71 mission at the base until 1990. Beginning in 1968, Beale also heavily supported the Vietnam War effort, with B-52s and KC-135s, additionally marshalling strategic reconnaissance with the SR-71s. In the middle 1970s, Strategic Air Command increased the reconnaissance role for Beale through the deployment of the U-2.

At this same time, planning began for placement of a PAVE PAWS radar on base, with local controversies over the issues of radiation. Construction for the large phased-array radar began in 1977. Strategic Air Command activated the 7th Missile Warning Squadron at the PAVE PAWS facility in 1979, with the unit declared operational in 1980. Beale's long and continuous role in strategic defense became even stronger with the addition of the PAVE PAWS. British TR-1s joined the American U-2s at Beale beginning in 1981. In 1983, the Air Force placed the 7th Missile Warning Squadron under the newly formed Space Command, removing it from Strategic Air Command. The PAVE PAWS became a tenant unit at Beale. In November 1985, the Air Force redesignated Space Command as Air Force Space Command. Strategic Air Command deactivated in 1992, and the newly established Air Combat Command became the host at Beale Air Force Base. By late 1994, only the U-2s and PAVE PAWS remained at Beale as active missions that historically are associated with the Cold War.

The 7th Missile Warning Squadron (Space Warning Squadron)

The 7th Missile Warning Squadron (now 7th Space Warning Squadron) staffs the Missile Warning Operations Center within the Beale PAVE PAWS, and in turn supports the Missile Warning Center of North American Air Defense Command (NORAD) at Cheyenne Mountain, Colorado. The Missile Warning Center at NORAD receives and evaluates information from a constellation of defense satellites and eight large phased-array radars. The radars form a network inside the continental United States (with radars in California, Florida, Massachusetts, and North Dakota), and beyond its borders (with radars in Alaska, the Aleutians, Greenland, and England (Air Force Space Command 1997; Singcaster 1997).

The 7th Missile Warning Squadron initiated formal operations at the Beale PAVE PAWS in mid-August 1980 (7th Missile Warning Squadron 1990, 3-5). The 7th Missile Warning Squadron tracked both foreign and domestic launches. The Air Force paid particular attention to launches from the Kapustin Yar and Tyurantum installations of the Soviet Union. The 7th Missile Warning Squadron also tracked launches from Vandenberg Air Force Base and the Navy's Missile Test Center at Point Mugu, both in southern California, and from the Kwajalein Atoll in the Marshall Islands. Early missile trackings from Vandenberg and Point Mugu included ones for Thor, Atlas, Titan, Minuteman, Scout, and Delta (7th Missile Warning Squadron 1980 – 1982). (7th Missile Warning Squadron 1981a, 22). Significant events at the Beale PAVE PAWS during 1980, 1981, and 1982 focused on shakedown exercises, transition to fully operational status, and training scenarios (7th Missile Warning Squadron 1980b, 3). By early 1981, the Beale PAVE PAWS had participated in the Strategic Air Command exercise Global Shield 81; tracked the Space Shuttle Columbia; and, achieved a new site record of 290 consecutive hours without "unscheduled system degradation." Global Shield exercises included specific wargame scenarios for PAVE PAWS radars, and were practice for the contingencies of attack (6th Missile Warning Squadron 1980a, 31-32, exhibit 25). In 1982, the Air Force formed Space Command, and in 1983 the Air Force transferred PAVE PAWS from Strategic Air Command to this major command. In 1986, the 7th Missile Warning Squadron at the Beale PAVE PAWS became a multi-national squadron, with both American and Canadian military personnel (Cross 1997).

A combat crew of the 7th Missile Warning Squadron first operated from the Tactical Operations Room, known as the Missile Warning Operations Center in 1998. The Missile Warning Operations Center was a secure, limited-access room on the fourth floor of Building 5760. Essentially an alert crew, the unit working in the Tactical Operations Center during the 1980s was a four-member team (in 1998, as a three-member team). In its initial configuration, the combat crew changed shifts every 12 hours. In 1998, the crew was renewed in three, eight-hour shifts. The historic four-member crew consisted of one officer and three enlisted personnel: the space systems director, the space systems director technician, the space surveillance console operator, and the missile warning console operator. The 1998 crew consisted of the commander, the crew chief, and the space console operator, with five operational crews available for rotation. The commander had responsibility for assessing the overall confidence of a missile warning event. "Confidence" represented the human analysis of machine-generated information, combined with all other known indicators and the immediate environment, to determine whether or not data is actual or false. In 1998, the timeframe for assessing confidence was 60 seconds. The commander was directly linked via a hotline to the Missile Warning Center in Cheyenne Mountain to discuss confidence, possible system degradation, and any pertinent data. The Air Force required that two members of the crew be in the room at all times, with the third available for return within a two-minute parameter. At the outset of operations, the Tactical Operations Room maintained six radar consoles, one for each of the four crew members, an additional one for the maintenance monitor console operator, and one extra as a backup or for training. In 1998, the consoles numbered five, with much the same functions (7th Missile Warning Squadron 1981b, 6 and 1981d, 5; Emich 1998; 9th Missile Warning Squadron 1986, 22).

In 1998, the PAVE PAWS at Beale Air Force Base sustained a near-earth surveillance fence, with 3,000 nautical miles coverage within the elevation and azimuth parameters defined by the radar's two arrays. If a detected object was not listed in a catalog of known objects, the PAVE PAWS computer determined if the object was on a ballistic trajectory—that is, on a course to impact the earth. The PAVE PAWS computer had an "orbital element set" of information for particular objects, and based its decision to track or not track on this information. The commander in the Missile Warning Operations Center in Building 5760 assessed the information as "valid," "under investigation," or "anomalous" (originally termed, "high confidence," "medium confidence," or "low confidence"). In addition to the tracking of SLBMs and ICBMs, the Beale PAVE PAWS also sustained a secondary mission to track space objects as they re-enter the near-earth atmosphere. In 1998, the Missile Warning Operations Center in Building 5760 received a task list at the beginning of each Zulu day, which identified satellites requiring tracking and specified the number of data sets that were needed for particular objects. The Missile Warning Operations Center tracked certain high-priority satellites with greater detail. The alert crew manually built individual fences, thus specifically directing a portion of the radar to capture the known satellites as they came into range of the Beale PAVE PAWS. The tracking load of the radar in 1998 was about 1,200 objects (7th Missile Warning Squadron 1982b, 24; Emich 1998).

Computer Operations for PAVE PAWS 1980-1987

In 1998, the Computer Maintenance Operations Center on the third floor of Building 5760 was the center of computer activities integral to the PAVE PAWS at Beale (7th Missile Warning Squadron 1981d, 7). The center, like the Missile Warning Operations Center, was a 24-hour-a-day operation with limited access. Personnel worked in eight-hour shifts.

During the 1980s, two important computer services squadrons were also located in the Beale PAVE PAWS, operating in a work space on the first floor of Building 5760. In a partnership between the military and private industry, the first programmers attended university classes to study operating systems and applications software within the PAVE PAWS system. The Air Force then assigned this group of programmers to the Beale PAVE PAWS as a part of the 7th Missile Warning Squadron in August 1979. With the placement of PAVE PAWS under Strategic Air Command at the end of the year, the computer services squadron at the Beale PAVE PAWS became an operational detachment of the 3900 Computer Services Squadron located at Strategic Air Command's headquarters at Offutt Air Force Base, Nebraska. The detachment of the 3900 Computer Services Squadron at the Beale PAVE PAWS had responsibility for developing all the modifications to software across the system, inclusive of that for the Cape Cod and Beale radars. The detachment also developed control language procedures and documentation, computer programmer test and evaluation, and integration test and evaluation. Control Data Corporation field representatives directly supported the detachment of the 3900 Computer Services Squadron at Beale in its opening months. Control Data developed the PAVE PAWS computer, the Cyber series. With the change of major command from Strategic Air Command to Space Command, the Detachment 2 of the 1020th Computer Services Squadron replaced the detachment of the 3900 Computer Services Squadron at Beale (1020th Computer Services Squadron 1983, 1-2).

VII. HISTORICAL CONTEXT – THE PAVE PAWS NETWORK

East and West PAVE PAWS, 1975-1980

The first two PAVE PAWS radars at Cape Cod and Beale represent a plateau in the development of large phased-array radars by the American military. In planning during 1974-1976, while the United States and the Soviet Union were modifying the ABM Treaty of 1972 with a Protocol, the PAVE PAWS network was to include four large phased-array radars. The Air Force sited the radars in the northeast, the northwest, the southeast, and the southwest of the continental United States. Like every air defense system before it, PAVE PAWS came to fruition in a downscaled version. Very high costs, as well as rapidly advancing radar and computer technologies partially account for the smaller number of radars. The planned PAVE PAWS radars were also controversial with respect to the ABM Treaty and its Protocol. The Air Force justified PAVE PAWS by describing the radars as a dedicated early warning system built along the periphery of the nation, not as long-range search radars within an ABM system. Both the United States and the Soviet Union understood that large phased-array radars, as components of an ABM system, were those structures that required the longest construction time. Denial of a future revamping of PAVE PAWS radars for a ballistic missile shield, as well as their possible battle management conversion capability, was debatable. As of 2000-2002, their reconfiguration for ballistic missile defense was a given.

The Air Force established PAVE PAWS as a radar surveillance fence around the North American land mass, positioning the radars to catch the trajectories of SLBMs launched from known Soviet ocean patrols. At the outset of planning for PAVE PAWS, the Air Force referenced the large phased-array radar at Eglin Air Force Base of the 1960s and the Cobra Dane large phased-array radar in the Aleutians of the early 1970s as the system's direct models (2nd Weather Squadron 1978, 1-3). The PAVE PAWS incorporated the following elements, all present at Cobra Dane:

- the truncated pyramidal form,
- the steel-frame, aluminum-paneled structure,
- the 20-degree angle of radar face,
- the independent power plant; the corporate feed system, and,
- field horns used for testing.

The chief distinctions of PAVE PAWS were its design with two radar faces and the shift from traveling wave tube technology to that of solid-state transmit-receive modules. Engineers reduced the number of field horns from both the near- and far-field horns at Cobra Dane, to just near-field horns at both Cape Cod and Beale. The dual design of the radar faces expanded azimuth coverage from 120 degrees to 240 degrees. Elevation coverage continued to match that of Cobra Dane, a feature determined by the angle of set back for the radar face. PAVE PAWS initiated the building of an American large phased-array radar network that would greatly overlap in its coverage, and thus could better survive planned enemy blackout and individual radar failure. Both the Cape Cod and Beale PAVE PAWS were also sited on hilltops, important to optimum working of the large phased-array radar.

Raytheon designed and built the Cape Cod and Beale PAVE PAWS as nearly identical. The Air Force declared the Cape Cod PAVE PAWS operational in April 1980, slightly in advance of operational status for Beale. Shakedown issues were similar at both installations, as was their participation in simulation and practice exercises. Cape Cod tracked American domestic ICBM launches from Cape Canaveral in Florida, as well as test SLBM and satellite launches. Beale performed parallel duties focused on launches from Vandenberg Air Force Base in southern California, also tracking Soviet launches. Computers installed for controlling both PAVE PAWS were the duplexed Cyber 170-174s (6th Missile Warning Squadron 1980a, 1980b, 1981). One distinction was the need for antenna element heaters at Cape Cod, with no need at Beale. Another was the maintenance required over time. More severe winter conditions at Cape Cod necessitated complete replacement of the outer aluminum paneling due to deterioration (Hall 1998). Cape Cod also has had problems with water leakage.

Southeast and Southwest PAVE PAWS, 1981-1987

In 1981, the Air Force formally announced its intention to deploy two additional PAVE PAWS in the southeastern and southwestern United States, performing a site survey in June 1981 for the southeast and in late 1982 for the southwest. For the third PAVE PAWS, two sites reached the final consideration stage, ones at Robins and Moody Air Force Bases in Georgia. For the fourth PAVE PAWS, three sites reached such consideration, those of the Mount Susan and Door Key ranch near Christoval, the Blaylock ranch in Schleicher County, and the Chandler ranch on the

Tom Green – Schleicher County line. In late 1983, Raytheon won the $77-million contract for the Georgia PAVE PAWS to be built at Robins, with contract award for the Texas radar following in 1984. Construction at both sites began in 1984. The Robins PAVE PAWS became operational in 1986; the Eldorado PAVE PAWS, in 1987. Raytheon designed the Robins PAVE PAWS to be more powerful, and more accurate in resolution, than the PAVE PAWS at Cape Cod and Beale. Air Force Space Command also assigned the Eldorado PAVE PAWS the mission of receiving alert messages from a regional Naval Space Surveillance System (NAVSPASUR) installation. NAVSPASUR is a Navy network of multi-static, continuous-wave radars scanning in one dimension.

The several-year window during which the Air Force built the Robins and Eldorado PAVE PAWS radars was a particularly complex one. In mid-1983, the Soviet Union began construction of its sixth Hen Roost large phased-array radar, at Abalakovo near Krasnoyarsk north of the Mongolian border. The Soviet action followed President Reagan's announcement the previous March that the United States planned to undertake research for a new space-based ABM system, the Strategic Defense Initiative (SDI). Reagan's SDI (Star Wars) speech had brought into question American upholding of Article V of the ABM Treaty of 1972, which prohibited the development, testing, and deployment of ABM systems or their components that are sea-, air-, space- or mobile land-based. Unlike any other Soviet early warning radar erected after the treaty, the Hen Roost radar at Abalakovo sits in the interior of the former Soviet Union, more than the stipulated 150 kilometers (about 93 miles) from a border. The radar is oriented inwards. In theory, these two conditions violated Article VI (b) of the treaty. The United States reacted immediately. Known as the Krasnoyarsk radar, the radar at Abalakovo became the focus of aggressive discussion. Additional American complaints followed in 1984 and 1985. As operational status of the Krasnoyarsk radar approached, the controversy grew more and more heated. While these issues were on the table, the United States awarded contracts to Raytheon for a PAVE PAWS-type radar at Thule Air Base in Greenland, to replace the 1960s BMEWS radars there, and for the third and fourth PAVE PAWS. Construction of large phased-array radars at Thule, Robins, and Eldorado began in 1984. The Texas and Georgia PAVE PAWS, like that at Krasnoyarsk, were controversial. The Air Force had not sited either immediate to the country's periphery, and each had some inland coverage. (The Georgia PAVE PAWS sits about 260 miles inland.) The Thule radar, argued as upgrading a pre-existing early warning radar, was equally debated for its location in a third country (Article IX of the ABM Treaty). International politics referenced the entire situation as "breakout" from the ABM Treaty, with repeated agreement that the large phased-array radars of both Hen Roost and PAVE PAWS, especially by the late 1980s, could function in either the early warning or battle management modes. (Carter and Schwartz 1984, appendix; Jasani 1987, 38-41; Rhinelander 1987, 154-155; Zaloga 1989, 144-145; Parrott 1987, 40-41; Bussert 1987, 122).

Most sources refer to the Robins and Eldorado PAVE PAWS as AN/FPS-115 radars, continuing the formal designation of the PAVE PAWS at Cape Cod and Beale. Nonetheless, military and Raytheon sources of 1986-1988, as well as today, describe the Robins and Eldorado PAVE PAWS as AN/FPS-123 radars. The AN/FPS-123 designation also applies to the large phased-array radar added at Thule, Greenland, at this same time. As of July 2000, Dr. Eli Brookner of Raytheon lists six large phased-array radars as either built or upgraded to AN/FPS-123s, including the four PAVE PAWS at Cape Cod, Beale, Robins, and Eldorado, and the upgraded BMEWS radars at Thule, Greenland, and Clear, Alaska (Brookner 2000b). The Robins and Eldorado PAVE PAWS retained the typical post-Cobra Dane design: a basic truncated pyramidal shape, with trapezoidal footprint; overall size parameters and construction system; a 20-degree setback; 420-450 MHz frequency; Cyber 170 computers; and, the dual radar arrays. As built, there was a visible distinction in the design of the individual radar faces at Robins, assumed tied to that radar's more powerful programmed decibel operation. The Cape Cod, Beale, and Eldorado PAVE PAWS presented simpler-shaped arrays, both in their outer aperture frames and in their presentation of antenna element slots (9th Missile Warning Squadron 1985 and 1986; *Aviation Week* 1983, 155; Air Force Space Command n.d.; Raytheon 1988, 1, 21, 58; Raytheon 1987, 2-27; Hoffecker and Whorton 1996, 79). The designation change from AN/FPS-115 to AN/FPS-123 for PAVE PAWS reflected steps toward fully upgrading the system. Radar technical literature described the improved PAVE PAWS in terms of numeric decibel power, which in turn translated to the number of individual dipole elements (antenna) activated on the radar's faces (Hall 1998; Raytheon 1988; Brookner 1988b, 124; 10th Missile Warning Squadron 1986, 24).

The third and fourth PAVE PAWS remained operational for only a few years. Military spending cutbacks and newly assessed needs led the Air Force to place these two radars in caretaker status during 1995. The Air Force considered both installations as sources for reusable radar components for the construction of a PAVE PAWS-type radar at Clear, Alaska, to replace the 1963 BMEWS installation there. Initial thinking was that Raytheon would remove parts from both the Robins and Eldorado PAVE PAWS, so that no party could interpret either as dismantled in the language of the ABM Treaty of 1972. Under stipulations of the treaty, neither the United States nor the Soviet Union could rebuild large phased-array radars once they were fully dismantled. As of 1998, however, the Air Force decided to reuse radar components only from the Eldorado facility, with crating to take place between July 1998 and March 1999 (Raytheon 1988, 1, 8; Burress 1998; Hall 1998; Air Force Materiel Command 1997; Raytheon 1987, 2-8, 2-9). As of 1999, the Air Force recategorized the Robins and Eldorado PAVE PAWS as in cold storage, without maintenance. That at Eldorado was partially dismantled; that at Robins, intact (Whorton 2000, 10).

Upgrades at the Cape Cod and Beale PAVE PAWS

In addition to the construction of a third and fourth PAVE PAWS in the continental United States, the Air Force also upgraded the original PAVE PAWS at Cape Cod and Beale between the late 1980s and the late 1990s. Plans for the first major improvements date to 1987, with Raytheon undertaking them between 1989 and 1991. The Air Force upgraded radar and computer equipment, and added more advanced software. With regard to the latter two items, Cyber 170-865s replaced the original Cyber 170-74s, making all four of the PAVE PAWS sites identical in their computer systems at the end of the Cold War. Both the PAVE PAWS at Cape Cod and Beale also received updated generators in their power plants. Other changes at the Cape Cod and Beale PAVE PAWS followed later in the decade. The second set of PAVE PAWS each featured three fuel tanks, instead of the four at Cape Cod and Beale. At Beale, the Air Force completed tank change-out to three tanks in September 1998. The late 1990s upgrade also planned to increase in the number of transmit-receive modules at the Beale PAVE PAWS. The Air Force intended to augment the Beale PAVE PAWS two-fold, to allow the facility to achieve a 6-decibel search status and a 9-decibel track status, should that increase in power be desired. As carried out, upgrade of the late 1990s did not increase the number of active antenna elements at Beale (Raytheon 1987, 1990; Wood 1998; Creek 1998). Another set of upgrades was underway in 1998.

VIII. HISTORICAL CONTEXT – THE SCIENTIFIC AND MILITARY SETTING

The scientific and military events that supported the development of American large phased-array radar, and PAVE PAWS in particular, were multi-faceted. Achievements in radar and computer technologies compounded steadily from World War II forward. The progression of ever-better radar and more advanced computers made PAVE PAWS possible. The world political stage, heightened through the escalating Cold War between the United States and the Soviet Union, also focused the radar needs of the American military. Large phased-array radars such as PAVE PAWS were pivotal for strategies of surveillance and counter-surveillance, weapons-use potential, and the particulars of the ABM Treaty. The close working relationships between the United States Army and its contractors, as well as those between the United States Air Force and its contractors, were also critical for the achievement of PAVE PAWS. Three themes emerge for understanding the broader setting of PAVE PAWS:

- key radar and computer developments of the 1950s-1970s leading to PAVE PAWS;
- the military industrial complex of the Cold War era – the military-contractor teams that made PAVE PAWS possible; and,
- sequential events of the Cold War tied to PAVE PAWS.

Encapsulated in the topical discussions below, these themes can be explored in more depth through references contained in the bibliography.

Radar and Computer Developments Leading to PAVE PAWS

American Cold War Radar Fences

Development of a Cold War radar fence for the North American continent began just after World War II. At the close of 1946, initial proposals called for a clustering of 24 radars to forewarn key areas in the United States of approaching bombers. These locations, the Northeast, the industrial upper Midwest, and the West Coast, concentrated on individual cities that sustained political and military assets. By 1947, another plan emerged for a more encompassing early warning radar network of 411 radars and 18 command and control centers (Winkler 1997, 16). The intent was for a joint American-Canadian radar fence. The neighboring governments largely planned radars and their control centers for American soil, but they earmarked about 9% of the radars and 22% of the control centers for Canada and Greenland (Weitze 1996, 24-25). During 1948, the international situation continued to worsen, especially in Eastern Europe, and stimulated more progress toward a radar fence. The Air Force called the first 24-hour alert of the Cold War in the Northwest and Alaska, with air defense games for the region following immediately (Schaffel 1991, 77-87). As 1948 continued to unravel, the Air Force expanded this temporary radar fence to include the Northeast and the Los Alamos-Albuquerque area. Formalized as the Lashup Radar Network, these first radar fences left much of the North American continent unprotected, yet set the precedent for the future (Weitze 1996, 25; Winkler 1997, 20).

Before 1948 closed, a more limited plan evolved for a permanent radar net in the United States and Alaska. During late August and September 1949, world events further escalated air defense worries for the American military. With the successful Soviet test of an atomic device and the fall of China to Communism, attention again focused on the need to erect radar installations for the North American continent. Air Defense Command set up air defense sectors throughout the

United States, covered by a variety of search and height-finder radars (Weitze 1996, 26, 40, 51; Winkler 1997, 20, 73-77). Joint protection of the North American continent continued to be an issue as 1950 unfolded. With the opening of the Korean War in June, the American and Canadian air forces agreed to the construction of a group of radar stations in Canada as a part of the Radar Extension Program (Jockel 1987, 49; Schaffel 1991, 121, 209-210). This radar fence was called the Pinetree Line, with more than 30 radars operational on both sides of the border in 1954. Continuing the trend toward extensive radar fencing across the north, scientists at McGill University in Montreal and at the Lincoln Laboratory at the Massachusetts Institute of Technology developed an aural presentation for radar, whereby aircraft flying into range would set off an alarm. This next fence northwards was known as the Mid-Canada Line, or McGill Fence. The northernmost fence was not sophisticated in its ability to screen, but also did not require manning. The Pinetree and McGill radar fences overlapped in their construction (Winkler 1997, 22; Jockel 1987, 49, 66; Schaffel 1991, 210).

During the middle 1950s, planning and construction for North American radar fences accelerated. Desire to place a fence to the far north, above the Arctic Circle across Alaska and Canada, resulted in the Distant Early Warning (DEW) Line. Construction for the DEW Line began in 1955, with completion in 1957 (Schaffel 1991, 211-217). Extremely difficult atmospheric conditions in the far north made a second system necessary, the White Alice Communications System (WACS). WACS used a forward propagation tropospheric scatter system to handle communications over very long distances under severe weather conditions and disturbances (Weitze 1992). With the exception of the unmanned McGill Fence, each of the 1950s radar fences relied on radar units for stations on American soil. By mid-decade, Air Defense Command was moving toward a computerized command and control for its radar network. Known as SAGE, the computerized control system came on line simultaneously with improved radars. Several of the radars within this group could shift frequencies, including the AN/FPS-24 (General Electric), the AN/FPS-27 (Westinghouse), and the AN/FPS-35 (Sperry) search radars (Winkler 1997, 77-83). The Air Force planned these radar fences, overseen through increasingly sophisticated control centers, to counter the Soviet bomber threat. Their value lessened with the advent of the ICBM.

Today the DEW Line radars continue as an active early warning radar fence, upgraded with newer, more sophisticated equipment. The system is typically referenced now as the North Warning System, rather than the DEW Line, and incorporates some physical site changes. The North Warning System, in its new configuration, was planned to be fully operational as of 1994. Another group of upgraded radars collated from the remnants of the original Supremacy Plan and the Pinetree Line, numbering about 60, also continues as a radar fence, with command and control shifting during the early 1980s from SAGE to the Joint [U.S.-Canadian] Surveillance System command and control system extant at six locations in the continental United States and Alaska/Hawaii, and at two Canadian sites (Mayfield 1980, 229-230; Blake 1995, 34).

The Need for BMEWS

Just as the early warning radar in the United States and the tiered fences across Canada were all made operational with computerized command and control through SAGE at the outset of the 1960s, air defense realities shifted. Military leaders and scientists understood that semi-hardened aboveground command and control would not likely survive an ICBM attack, and made plans to place a centralized command post within Cheyenne Mountain. Construction for this facility occupied years, and it was not until 1966 that this next generation of command and control achieved full completion (Winkler 1997, 44-45). Planning for Cheyenne Mountain dates to the middle 1950s, when the Air Force simultaneously called for a ballistic missile detection system establishing three radar sites to the very, very far north, at and beyond the DEW Line. After the Soviet launching of Sputnik in October 1957, the Air Force planned for BMEWS, laying out the site choices as Clear, Alaska; Thule, Greenland; and, Fylingdales Moor, England. At this same time, the United States discovered that the Soviet Union had significantly advanced its radar capabilities with an eye toward ballistic missiles. The three BMEWS radars were under construction in 1958, with Thule operational in late 1960, Clear in mid-1961, and Fylingdales Moor in autumn 1963 (Schaffel 1991, 259-261; Stein 1984, 87). The BMEWS radars were UHF 425-450 MHz equipment, and were large. The AN/FPS-49 was a mechanically-steered radar sheathed in a radome, installed at Thule (one) and Fylingdales Moor (three), while the AN/FPS-50 was a fixed-fence radar, standing 165' tall and 400' wide, and operating through line-of-sight. This radar scanned 40 degrees in azimuth, and featured two radar beams at two elevation angles. The upper beam fanned at a seven-degree elevation, the lower at 3.5 degrees. The Thule site included four AN/FPS-50s; the Clear site, three. The grouping of three AN/FPS-50s at Clear, for example, together created an azimuth capability of 120 degrees, identical to a single face of the Beale PAVE PAWS. The four-radar cluster at Thule monitored 160 degrees in azimuth. That at Fylingdales Moor had no search radars, hosting only its three AN/FPS-49s (Space Policy Project 1999 and Brookner 2000a).

The BMEWS AN/FPS-50 radars directly foreshadowed five key elements of early warning radar from about 1963 forward:

- the number of radar installations making up the network would be much smaller, with each covering more territory and with radars achieving very large individual size;
- computers and their software would have the potential to upgrade the facilities markedly over time;
- the radars would operate in the 400+ MHz range, with visible objects 3,000 miles distant;
- speed for tracking multiple objects, coupled with battle management decision-making capabilities, would be needed at the radars themselves; and,
- command and control would become most effective in a central installation at Cheyenne Mountain, one hardened below ground to survive attack, with additional direct links to Strategic Air Command's underground command post at its Headquarters at Offutt Air Force Base in Nebraska.

From this point on, early warning radars were intimately linked with ballistic missile defense, and were the bedrock infrastructure, along with advancing ICBM systems themselves, for what can be described as the second half of the Cold War.

BMEWS Upgrades and PAVE PAWS

Upgrading of BMEWS in Greenland, England, and Alaska closely followed upon PAVE PAWS and is directly related to the four-radar network. Contracted in July 1983, the Thule PAVE PAWS-like radar achieved operational capability in 1987. The Thule radar is somewhat different from the four PAVE PAWS in its physical detailing and in its element configuration, although continues the key attributes of the large phased-array radar network. The radar sits atop an existing four-story rectangular building, a structure intended to serve as a base for a second

AN/FPS-49 (never-deployed) (Stein 1984, 87, 91; *Defense Electronics* 1985, 103; Brookner 1988b, 32-33; Painter 1988, 73; Hall 1998; Hoffecker and Whorton 1996, 38). In mid-1988, Raytheon won the $166.8 million contract to replace the three AN/FPS-49s at Fylingdales Moor with a PAVE PAWS-like radar as a part of the continuing BMEWS upgrade. The Fylingdales Moor large phased-array radar is the first of the PAVE PAWS and BMEWS radars to have three radar faces, with 360 degrees of coverage in azimuth. The Fylingdales Moor radar became operational in late 1992. Due to its disposition on foreign soil, the Fylingdales Moor radar was controversial concerning Article VI(b) and Article IX of the ABM Treaty of 1972. Some analysts also interpreted the radar as violating Agreed Statement F of the treaty, due the radar's total power potential (Blake 1995, 34, 90; Rhinelander 1987, 154). Raytheon won the contract for the final BMEWS upgrade at Clear in 1997. The Air Force chose to dismantle the PAVE PAWS at Eldorado, reusing its parts in a new building at the Alaska site. Construction crews began work at Clear in April 1998, finishing the radar in 2000. After a year of shakedown tests, the large phased-array radar at Clear became operational in December 2000. The reconstituted PAVE PAWS erected at Clear for the upgraded BMEWS also included an SLBM long-range search-and-track mission, again paralleling the original PAVE PAWS of the 1970s and 1980s. By February 2001, the Fairbanks newspaper noted that the Clear large, phased-array radar would "feed and cue the interceptor's radar," should the Army build a ballistic missile defense system (Air Force Materiel Command 1997; Hall 1998; *Fairbanks Daily News-Miner* 2001).

Evolution of Scientific Mainframes and Supercomputers

Beginning with studies in 1949 to adapt advances of World War II to the needs of early warning air defense radar, computer projects in government and corporate laboratories steadily led to the duplexed systems employed in the PAVE PAWS. The Air Force set up the Air Defense System Engineering Committee in that year, headed by physics professor George E. Valley of the Massachusetts Institute of Technology. Better known as the Valley Committee, this task force reviewed cutting-edge computer air defense work. Among the most impressive efforts was that of Raytheon, who was then designing the Hurricane computer for real-time air defense problems focused on the guidance of short-range missiles. The Hurricane staff was also theorizing about automatic tracking radars before 1950 (Valley 1985, 207). In this heady period too, the Air Force adapted the Navy's Project Whirlwind computer developed by the Massachusetts Institute of Technology's Digital Computer Laboratory for its air defense purposes, setting up Project Charles in early 1951. Turning to a Navy project for its air defense computer technology was not all that surprising. Radar, greatly advanced during World War II, shared many systems needs with early computer engineering, and linked the two arenas from the start (Jacobs 1983, 324-325; Valley 1985; Ceruzzi 1989).

The mature air defense project SAGE, overseen by the Massachusetts Institute of Technology's Lincoln Laboratory and coordinated through the Cambridge Research Laboratories at Hanscom Air Force Base, was perhaps the most important forbearer in the race toward the supercomputer. SAGE relied on two IBM computers, the AN/FSQ-7 and the AN/FSQ-8 (Astrahan and Jacobs 1983, 343-344). The Air Force always used these machines in a duplex format, with two redundant machines in place, one active and one as backup (Weitze 1996, 54-56). The technological advancements leading to SAGE, as well as the procedures developed for computer use in air defense, set the stage for the advancements and procedures needed for PAVE PAWS. The AN/FSQ-7 was one of the earliest production computers to incorporate random-access core memory (RAM). It also incorporated a dual arithmetic element that processed the X and Y positions of data simultaneously, allowing greatly enhanced speed (Jacobs 1983, 325). The AN/FSQ-7 entered the commercial sector in 1954-1955 as IBM's 704 computer (*Annals of the History of Computing* 1987, 108). During the second half of the 1950s, the category of supercomputer emerged. Generally, the military and its affiliates interpreted the IBM 701 (1952), the IBM 704 (1954-1955), and the IBM 709 (by 1959) as scientific computers (MacKenzie 1991, 180; *Annals of the History of Computing* 1987, 108). During the late 1950s and the early 1960s, further efforts toward development of a very fast computer able to handle large numbers of complex calculations continued, with the Univac, the Remington Rand Livermore Automatic Research Computer and the IBM Stretch computers leading the way. By the close of 1960, the IBM 7090 continued that company's evolution through its 700 series, again pushing the boundaries of the scientific computer (Murray 1997, 74; Thornton 1980, 338). The breakthrough to the true supercomputer came from the Control Data Corporation in 1964, with Seymour Cray's CDC 6600. Control Data's machine took much of the lead from IBM in the supercomputer race, itself largely driven by Cold War military needs and air defense/nuclear weapons issues (Murray 1997, 107-109).

The demands of the Los Alamos and Livermore Laboratories drove developments in supercomputer technology. Among the first assignments for the 1946 ENIAC (Electronic Numerical Integrator and Calculator), really an advanced calculator, had been hydrogen bomb simulations. Not surprisingly then, computer development for the large phased-array radar was directly tied to first studies and experimentation for ABM computers. In a project for the Army, Control Data studied the large phased-array radar at Eglin Air Force Base and the radar set up for ABM studies on the Kwajalein Atoll in the Marshall Islands, along with other selected advanced radars. The Army directed Control Data to develop a computer system for a missile-commanding radar of 1,500-mile range. The desired computer had to be able to achieve surveillance, tracking, and discrimination, to handle countermeasures, to guide missiles, and to dump power (Control Data Corporation 1969). Control Data's work for the Army led directly to the company's Cyber series (MacKenzie 1991, 192), the series from which the Air Force drew its original computers for PAVE PAWS. The first early warning network incorporating the scientific mainframe was BMEWS, with the radars at Thule, Fylingdales Moor, and Clear each having duplexed IBM 7090s (Stein 1984, 87).

By the middle 1970s, a mature system of computers appropriate for the early warning and tracking mission appeared. Cobra Dane, in design in 1973 and operational in 1977, featured the first generation of Cybers, from the Control Data Cyber 70 series. With design and development for PAVE PAWS during the middle and late 1970s, the Air Force upgraded the duplexed computer to the next Cyber generation, the Cyber 170 series. The Cyber 170s specifically installed at Cape Cod and Beale Air Force Bases were Cyber 170-174s, the latter numerical designator an indicator of upgraded peripheral processing units for the series. The Cyber 170 series has been long-lived for American large phased-array radars. Major upgrades for PAVE PAWS, including the as-built construction for Robins and Eldorado, as well as the upgrading of each of the BMEWS radars, have all been Cyber 170s (Heath 1998). In 1983, the Beale PAVE PAWS also added a CDC 170-720 to its duplexed Cyber 170-174s (1020th Computer Services Squadron 1983, 8). With construction of the third and fourth PAVE PAWS at Robins and Eldorado in the middle 1980s, and the first replacement of the radars at the Thule BMEWS site with a large phased-array radar at the same time, the Air Force installed duplexed Cyber 170-865s (Judge 1985, 92; Stein 1984, 87, 91). The major upgrade at the Cape Cod and Beale PAVE

PAWS, as well as the construction of a large, phased-array radar for Fylingdales Moor, occurred in the late 1980s and in the early 1990s, again with duplexed Cyber 170-865s the choice.

The development of the military large scientific computer, and much of the work carried out for the first supercomputers associated with nuclear weapons design and ABM, is directly tied to the technological achievement of the large phased-array radar. Early large phased-array radars used what was then state-of-the-art. The radars' duplexed computers followed the pattern initially set up by SAGE in the late 1950s. The Air Force has consistently upgraded the computer systems at each of its large phased-array radars, both in hardware and software. These upgrades are integral to the continued technological achievements of the PAVE PAWS at Beale.

The Military Industrial Complex and PAVE PAWS

Bell, Raytheon, and Bendix

Radar research and development has grown steadily from the 1920s through today, with the three most important corporate contributors to prototype testing and development of large phased-array radar those of Bell, Raytheon, and Bendix. Bell and Raytheon were key contractors for the Army, while Bendix filled a parallel role for the Air Force. American Telegraph &Telephone (AT&T) had led radio research during the 1920s, establishing their Bell Telephone Laboratories in that decade. By the 1930s, Bell undertook radar research, switching to military development and production during World War II. Bell designed the military radars, while the manufacturing arm of AT&T, the Western Electric Company, built them. Also dating back to the outset of the 1920s are the contributions of Raytheon. Founded in Cambridge, Massachusetts, in 1922 by Laurence K. Marshall and Dr. C.G. Smith, Raytheon first called itself the American Research and Development Corporation. In 1925, the company adopted the name Raytheon, producing the first gas-filled rectifier tube. During World War II, the National Defense Research Council (NDRC) contracted with Raytheon to develop and manufacture radar equipment. NDRC's selection of Raytheon, like the military choice of Bell Laboratories, placed the company in a prime position at the outset of the Cold War (Gross, Hall and Barton 1974, 2; Painter 1988, 67-68; Bruce-Briggs 1988, 26-28.)

Both Bell and Raytheon were among the first companies to conceptualize radars for missile guidance and air defense. An ordnance officer at the Frankford Arsenal in Philadelphia, Jake Schaefer, began to work on problems of early warning and tracking via radar, connected to those of radar-guided missile defense. Schaefer was on a leave of absence from Bell while in the service during World War II (Bruce-Briggs 1988, 46-47). Post-war, the American government acquired German equipment and supporting documentation. Hundreds of high-level German scientists and engineers came to the United States in the late 1940s under Project Paperclip. Most of these men (and several women) worked for the Army, Air Force, and Navy, but from the beginning the government placed a number within companies that contracted to the military. By the late 1950s, after achieving American citizenship, many Paperclippers left civil service for work with aerospace contractors. Raytheon hired Dr. Martin Schilling in 1958, when the company's Missile Systems Division began to work on the antiballistic problem (Raytheon 1976, 30). Almost immediately, Dr. Schilling expressed an interest in phased-array radar theory, and led Raytheon in that direction for research and development. In 1961, the Department of Defense contracted with Raytheon to prepare a study for a ballistic missile attack warning system (Raytheon 1961). Dr. Schilling also steered Raytheon to winning the subcontract for the traveling wave tubes (Dashefsky and Derby 1976, 8-9). Raytheon next had the opportunity to propose on a subcontract to Bell Laboratories for the development of the Missile Site Radar for the planned ABM program—what would ultimately be deployed as the Sentinel/Safeguard system in North Dakota. Raytheon ultimately worked on not just the Missile Site Radar, but also received the $39.5-million contract for Cobra Dane in 1973 (Del Papa 1991, 35).

Air Force Research and Development for Phased-Array Radar

While the Army tackled the challenge of large phased-array radar for its ballistic missile defense needs, the Air Force pursued parallel research toward advanced radar for missile-launch monitoring, and for tracking space objects. As early as 1954, the Air Force achieved the successful application of traveling wave tube technology to radar systems through work with Raytheon. In 1955, Avco established an experimental program for electronically steerable phased-array radar for the Air Force at the company's test site near Cincinnati. As of 1958-1959, the Air Force oversaw testing of RCA's AN/FPS-49 and General Electric's AN/FPS-50 radars at a prototype site for BMEWS located in Trinidad, also directing Bendix's testing of an electronically-steered radar at its company test site in Maryland. The Avco and Bendix experimental radars were linear precursors to the large phased-array radar that would mature as PAVE PAWS and upgraded BMEWS. The Air Force hired Bendix to develop the AN/FPS-85, the large phased-array radar placed at Eglin Air Force Base in the early 1960s. Air Force research and development also contributed to the Army's efforts, inclusive of the prototype large phased-array radar for ballistic missile defense erected on the Kwajalein Atoll in 1968. The Air Force referenced this radar, contracted to Hughes, as the Advanced Design Array Radar (Thompson and Scott 1986). The Air Force received responsibility for the Cobra Dane radar as of 1972 (contracting to Raytheon), and for the "design, fabrication, installation, integration test, and evaluation" of PAVE PAWS as of June 1975 (Smith and Byrd 1991, 123 and 141). The Air Force had first called the program SPARS, renaming it PAVE PAWS during the previous February (Del Papa 1991, 37). Acronym definition of SPARS remains undetermined.

Cold War Events Tied to PAVE PAWS

Weapons and Counter-Weapons / Surveillance and Counter-Surveillance

Two primary stimuli pushed the development and testing of the American large phased-array radar: Soviet progress toward ballistic missile defense, and Soviet advancements in SLBMs. By 1960, many radar electronics engineers understood that phased-array radar would become the next definition of modern radar. Much of the transition that occurred from mechanically-steered radar to phased-array radar awaited development of an electronic ferrite phase-shifter and the appropriate digital computer. Underpinning defense funding of the large phased-array radar were:

- the Cold War race to ICBMs and satellites during the late 1950s (Lonnquest and Winkler 1996);
- the discovery of a Soviet very large early warning radar network going in place simultaneously;
- the deployment of an ABM system around Moscow in 1964; and,
- Soviet advancements in SLBMs by the early 1970s (Stark 1974, 1661-1662, 1684-1685; Barton 1984, 1165; Skolnik 1985, 186).

The Soviet Union had planned for an ABM system as early as 1953, paralleling rapid American weapons development. During the early 1950s, the United States extended its radar network, but assumed that the potential threat was Soviet bombers and that the American military would prevail for some years in the weapons race. Yet in 1954-1955, the Soviets began construction of an ABM testing ground near Sary-Shagan, in Kazakhstan, following this activity in 1957 with the launching of the world's first ICBM and the Sputnik satellite (Weitze 1996, 28-31). The successful Soviet weapons development caused consternation in the United States, but the success of Sputnik and the late 1950s discovery of a system of very large radars under construction on Soviet soil caused real surprise. The situation stimulated Air Force research and development toward the phased-array radar, and also encouraged funding for BMEWS at Thule, Fylingdales Moor, and Clear. The Soviet radar, named Hen House by American analysts, was of fixed billboard type, but was much larger than anything previously known. Between 1955 and 1970, the Soviets built five Hen House radars around the periphery of the Eurasian land mass, with another six constructed in the early 1970s. The 11 radars were sited at six locations (Bussert 1987, 122; Blake 1995, 47; Zaloga 1989, 125-126). By the early 1960s, a need for ballistic missile defense stimulated the United States to begin serious efforts toward an ABM system and its associated large phased-array radars. In about 1970, the Air Force instituted the Cobra intelligence-gathering program, contracting for a series of surveillance projects focused on ICBM launches from the southwestern Soviet Union to the Kamchatka peninsula. As of early 1972, the agency began work toward the Cobra Dane large phased-array radar in the Aleutians (Smith and Byrd 1991, 123). The Cobra program went forward simultaneously with that for ballistic missile defense.

Impetus for expansion of the large phased-array radar network for the North American continent came in the middle 1980s. PAVE PAWS plans for a third and fourth site were set by the early 1980s, but it was not until after American satellites picked up a new, very large radar at Krasnoyarck during the summer of 1983, a large phased-array radar directly comparable to those of PAVE PAWS, that Congress funded the expensive construction. The Krasnoyarck radar was the sixth of what ultimately would become 10 Soviet ballistic-missile early warning radars. Construction of this system of large phased-array radars had begun in 1978, at Pechora. American analysts named the network Hen Roost. The Krasnoyarck radar stirred international allegations that it represented a Soviet breakout from the 1972 ABM Treaty and its follow-on Protocols and Agreed Statements. The Krasnoyarck radar was not on the geographic edge of the Soviet land mass, nor was it oriented outward (both treaty conditions). The Krasnoyarck radar was thought to be a battle-management radar, in addition to its functioning as a detection and tracking radar. Anxieties went higher with the knowledge that neither the longer-range SLBMs of the United States, nor those of the Soviets were of precision accuracy. In addition, communications with submarines were hard to maintain in a crisis, so that either side might over-react and launch, making the large phased-array radars of both nations a priority (Bruce-Briggs 1988, 400, 440; Jasani 1987, 24).

While the Soviets continued building their Hen Roost system, the Air Force finished PAVE PAWS and began to upgrade BMEWS to PAVE PAWS-type large phased-array radars. The BMEWS upgrades of the late 1980s and 1990s were not only for ICBM warning, but also for SLBM warning for the United States, England, and American forces in Europe (*Aviation Week* 1980, 241). Construction of large phased-array radars during the 1985-1991 period, that is up through the end of the Cold War, was intense in both the United States and the former Soviet Union. In addition to the SLBM threat, both countries were working on deployment of a rail-mobile ICBM launch capability for the multiple-warhead Peacekeeper and SS-24. In 1986, the Soviet rail-mobile system was operational. During the same year, President Reagan announced the Rail Garrison program. With ICBMs able to be launched from an unpredictable variety of sites, the need for large phased-array radars escalated enormously. It is no coincidence that the weapons systems and the large phased-array radars remained linked, construed to be counterparts to one another – the strategic weapons on the one hand and the radars, the most important component of either country's future ABM system, on the other.

From Sentinel to Safeguard

After the successful launching of the Sputnik satellite in October 1957, the Department of Defense established a service-independent body to undertake high-tech research, the Advanced Research Projects Agency (ARPA). ARPA immediately acquired responsibility for ballistic missile research, and at the close of the decade chose Roi-Namur Island in the Kwajalein Atoll of the Marshall Islands as the site of related test facilities. In 1960, the United States Army and Bell Laboratories took possession of the Kwajalein Atoll. The first radars built for work there were the Zeus Acquisition Radar, a fixed-fence tracking radar that accompanied the development of the Nike-Zeus antiballistic missile, and the Multi-function Array Radar I. Between 1960 and 1965, experimentation with these nascent large phased-array radars moved rapidly, with several overlapping efforts connected to ballistic missile defense. The Zeus Acquisition Radar on Kwajalein burned in early 1962, to be replaced by the first Perimeter Acquisition Radar designed for the next generation Nike, the Nike-X. The prototype Perimeter Acquisition Radar was not built at Kwajalein, but rather in the continental United States at White Sands Missile Range in New Mexico. A Multi-function Array Radar II was partially constructed at Kwajalein before it was abandoned as a prototype, its planned functions incorporated in the prototype Perimeter Acquisition Radar (Amitay, Galindo and Wu 1972, 2; Bruce-Briggs 1988).

For a few years in the early-to-middle 1960s, the planned ABM system (then called Sentinel) was to have three large phased-array radars: the Multi-function Array Radar, the Perimeter Acquisition Radar, and the Missile Site Radar. As finalized, the Army combined the Multi-function Array Radar and Perimeter Acquisition Radar into a single structure. Bell subcontracted to General Electric for its design (Brookner 1977, 27). Raytheon won the contract for the Missile Site Radar from Bell in 1963, and used its in-house phased-array research to develop the radar. Raytheon built a prototype Missile Site Radar for the Army on a second island, Meck, in the Kwajalein Atoll, during 1963-1965. After the decision to develop the Sentinel/Safeguard system with just the two radar types, the Perimeter Acquisition Radar and Missile Site Radar, the military converted the Multi-function Array Radar I on Kwajalein to the Common Aperture Multi-function Array Radar to serve as the technological test facility for Cobra Dane. In 1974, Raytheon described the lineage of the large phased-array radar as a branching tree, with the Multi-function Array Radar, Perimeter Acquisition Radar, and Missile Site Radar all connected, but with the final outcome as two separate branches. The Multi-function Array Radar and Perimeter Acquisition Radar led directly to the Common Aperture Multi-function Array Radar, thence to Cobra Dane, and finally to PAVE PAWS (Amitay, Galindo and Wu 1972, 4; Bruce-Briggs 1988, 246-252, 288-289; Gross, Hall and Barton 1974, 3-5).

As the experimentation at Kwajalein and White Sands settled out, the ballistic missile defense radars were of two types, the UHF (400-450 MHz) Perimeter Acquisition Radar for long-range search, acquisition and tracking of incoming enemy ICBMs and SLBMs, and the Missile Site

Radar, an S-band (2000-4000 MHz) short-range, track-and-guidance battle management radar. The Missile Site Radar was distinguished from the Perimeter Acquisition Radar in its precision tracking: it had less range capability, but higher resolution. The mission of the Perimeter Acquisition Radar was to warn of long-range threat, providing "area defense" by passing information to the Missile Site Radar and its affiliated long-range defense antiballistic missiles, the Spartans. Spartans were intended to take out enemy ICBMs high above the atmosphere. The final defense was guidance of the short-ranged Sprint antiballistic missiles, again through the Missile Site Radar, after the ICBMs had entered the atmosphere and been sorted out from confusion objects.

By the time the Sentinel/Safeguard Perimeter Acquisition Radar was ready to go to construction, research for the large phased-array radar had advanced considerably, with varying arguments for its design and working parts. One closely analyzed issue focused on transmitter components: use of traveling wave tubes as on the Kwajalein Atoll, versus use of tetrode tubes as at Eglin, versus solid-state modules. For the Perimeter Acquisition Radar, General Electric continued to incorporate the Raytheon traveling wave tube. The rationale was greater overall system flexibility and lower cost (Johnson 1970, 37-39). Cobra Dane would make the change from a hardened infrastructure to aluminum-paneled steel-frame, which had been foreshadowed in the large phased- array radar at Eglin, but it would not be until PAVE PAWS that the shift from tube technology to solid-state transmit-receive modules occurred. During the early planning stages for ABM, the Army envisioned the system as quite large, with 16 Missile Site Radars and their accompanying missile installations, and seven Perimeter Acquisition Radars "deployed around the perimeter of the country" (just as PAVE PAWS and the Soviet Hen Roost would be configured by the late 1980s). First site choices were nearly all in proximity to large cities. After President Nixon changed the ABM program from Sentinel to Safeguard in 1968, site choices shifted from ones near cities to ones near ICBM silos, with a downsizing in the number of proposed locations (Johnson 1970, 32-35). In large part due to the ABM Treaty of 1972, the Army only constructed one Safeguard site, that in the vicinity of Grand Forks Air Force Base in North Dakota.

Safeguard became operational in North Dakota in 1975, but was turned off the next year. Although the ABM Treaty of 1972 specifically allowed the United States and the Soviet Union to each build and maintain two ABM sites, one around their respective capitals, and one at an ICBM silo field, the United States chose to protect one missile field. The Soviet Union selected its capital, concentrating military buildup in other arenas. At the close of 1974, the Army made major modifications to the prototype Missile Site Radar in the Kwajalein Atoll, and continued to use it for ABM testing (Brookner 1977, 26). In 1976, the Army gutted the Missile Site Radar in North Dakota, with the Army shipping radar components to the construction site for Cobra Dane. The Army transferred the Safeguard Perimeter Acquisition Radar to the Air Force. After major modifications, the Safeguard Perimeter Acquisition Radar took on an early warning role for air defense (Bruce-Briggs 1988, 289-299, 326-337; Durch 1988, 47).

Effects of the Antiballistic Missile Treaty of 1972

Even as the Army's Safeguard system was under construction near Grand Forks, and as the Air Force AN/FPS-85 radar at Eglin was still in its shakedown period, international events seriously changed the planned development for American large phased-array radars. An enormous public debate had occurred during the late 1960s that focused on the very high costs of ballistic missile defense; on its technical uncertainties; on the possibility that a large-scale enemy attack could overwhelm even the best ABM installations; and, on the understanding that use of such a system required nuclear detonations on or above American soil. In 1969, the Soviet Union began negotiation with the United States for ABM limitations. The rationale for this step is highly debated. The Soviet Union already had an operational ABM system around Moscow, in place since 1964, and had nearly completed ringing its land mass with the Hen House early warning radars. Although the technology of Hen House did not match that of the planned Sentinel / Safeguard system, nor that of the AN/FPS-85 at Eglin, the key time-consuming components of an ABM system were there for potential upgrading. Articles in the open literature have argued that the Soviet Union did not want to continue huge ABM costs, paralleling a concern in the United States. Analysts also have made the case that the Soviet Union wanted a delay period of 10 to 15 years within which it could catch up in ABM technology, a period wherein the Soviet military could continue research and development, possibly transferring American technical advancements to Soviet systems. In any case, both countries came to the table for the ABM Treaty of 1972, returning in the years following for the addition of a number of classified addenda (Gaffney 1987, 282-283).

The ABM Treaty of May 1972 banned territorial defense against ICBMs, in theory making both the United States and the Soviet Union equally vulnerable should attack and counter-attack occur (Jasani 1987, 38; Carter and Schwartz 1984, appendix). As originally drafted and ratified, the ABM Treaty also had a series of specific Articles and Agreed Statements that further defined how large phased-array radars would be handled. During treaty negotiations, representatives of both countries understood that Perimeter Acquisition Radars could detect and track ICBMs, making them a particularly important asset in any long-term ABM system. The ABM Treaty required both countries to formally review its provisions every five years, and was of unlimited duration (Schneiter 1984). The treaty Articles most pertinent to the radar debate were I, VI, and IX, and Agreed Statements F and G. Article I (2) of the treaty prohibited each country from providing a "base" for an ABM system, but did not define what constituted such a base. Article VI (a) prohibited the upgrading of non-ABM systems by either giving them the capabilities to counter ICBMs or by testing them in an ABM mode. Article VI (b) limited the deployment of large phased-array radars for early warning of ICBMs to locations along the periphery of the national territory and required that they be oriented outwards, away from the nation's interior. Article IX prohibited deployment of, or transferring of ABM components to, third countries. As might be expected, these treaty items were open to interpretation, and were further limited as time passed.

In 1974 and afterwards, the United States and the Soviet Union significantly modified the ABM Treaty. An attached Protocol amended the treaty to allow only one ABM site per country. The Soviet Union chose to keep its ABM system around Moscow, and the United States its system in North Dakota (Jasani 1987, 38). The two countries agreed to the Protocol in 1974, with its entering into force in mid-1976. The 1974/1976 Protocol also discussed appropriate procedures for replacement and dismantling of ABM systems. In 1976, the United States chose to dismantle its North Dakota Safeguard site and transferred the Safeguard Perimeter Acquisition Radar to the Air Force as an early warning tracking radar. A coordinating committee comprised of members from both countries continued to meet after 1976 (Rhinelander 1987; Schneiter 1984; Carter and Schwartz 1984, appendix).

For both the Soviet Union and the United States, and with reference to the PAVE PAWS and upgraded BMEWS radars explicitly, several items of interpretation steadily surfaced. Questions raised include ones focused on the location of large phased-array radars along the outer periphery of either country, facing outward; the definition of what constitutes ABM components; deployment or transfer of ABM components to third countries; the interpretation of battle management capabilities and the base of an ABM system; the interpretation of potential reconfigurations of power and frequencies, based on aperture size, number of antennas, and computer capabilities; and, the validity of upgrading an existing large, early warning radar from non phased-array to a large phased-array radar (Jasani 1987, 24, 41; Rhinelander 1987). After the Cold War formally ended in 1991, these issues submerged for a brief period. Toward the end of the decade, a new situation evolved. Several of the Soviet Hen Roost radars were geographically outside the land mass of Russia, albeit were situated within the borders of countries formerly within the Soviet Union. Not all remained operational. By the close of the 1990s, the United States expressed concern about rogue countries' acquisition of ICBMs, and again desired to deploy a ballistic missile defense shield. This return to ABM defense led to an announcement by President George W. Bush on 13 December 2001 that the United States would exit from the 1972 ABM Treaty. Six months later, on 13 June 2002, the action became official, with immediate ground breaking in Alaska for six underground silos for missile interceptors (Sanger 2001; Sanger and Wines 2002). The active American large phased-array radars, inclusive of the two remaining PAVE PAWS, are a part of the current ballistic missile defense effort.

The Threat of SLBMs

Interspersed with events surrounding the Soviet-American race to test and implement an ABM program between the late 1950s and the early 1970s, another major stimulus for development of the large phased-array radar was the realization that the Soviet Union was working toward achievement of an SLBM. As early as November 1963, Headquarters Air Force had issued a directive calling for the development of an SLBM detection and warning system. By August 1966, testing was underway. The SS-N-5 and the SS-N-6 armed the Soviet Yankee class nuclear submarine as the late 1960s. The 750-mile and 1,300-mile Soviet SLBMs carried nuclear warheads, and fired submerged. Aircraft radar could not track them. In 1967, the Air Force put in place an interim detection and tracking radar system utilizing existing traditional radars, while efforts went forward toward the large phased-array radar network that would be PAVE PAWS. By 1973-1974, Soviet SLBMs were positioned both east and west of the continental United States in sizable numbers, and represented a complex tactical problem. The Delta class of nuclear submarines joined the Yankee class in the early 1970s, carrying the world's first long-range SLBM, the SS-N-8 (4,300 miles). The armed submarines meant that the Soviet Union could strike from a variety of changing positions. The United States did not achieve a comparable long-range SLBM until the Trident C-4 in the early 1980s (Hoffecker and Whorton 1996, 85-86; Burress 1998). The Soviet SLBM threat of the 1970s led directly to the funding for PAVE PAWS, with preliminary work for the system underway at mid-decade.

The Counterpoint of Soviet Missile-Detection Radar Development, 1954-2001

Military analysts date Soviet planning for an ABM system to the late 1940s. Missile and radar engineers consulted together, with the specific inclusion of advice from the German Peenemünde scientists gathered by the Soviets on Gorodomlya Island outside Moscow. (These men were the counterparts to the Paperclippers brought to the United States.) In the early 1950s a state program for anti-missile defense brought together Soviet scientists, engineers, and military officials. As was true in the United States, the program quickly focused on the two most formidable problems associated with the development of ballistic missile defense: the long range surveillance radars and the sophisticated computers required to operate the system. Two electronics engineers, Alexander L. Mints and General Grigorii V. Kisunko, led initial Soviet efforts, putting together alternate plans for ballistic missile defense. In 1954, the Soviet Union began to implement General Kisunko's plan. Analysts believe that F.V. Lukin directed the radar effort at the NII-37 research institute in Moscow, while V.S. Burtsev is thought to have managed the development of computer command and control. Soviet air defense districts, similar to those in the United States, were subdivided as zones and sectors (Zaloga 1989, 118-119; Blake 1995, 13).

The first Soviet early-warning radar network was that of Hen House, so named by Western intelligence. Analysts consider Hen House to have been a cross between a long-range, surveillance radar system like that of the early 1960s BMEWS and the AN/FPS-85 radar at Eglin. Hen House was a VHF (150 MHz) fixed, billboard-array radar, large in physical configuration and typically comprised of two arrays at each site. Radar face inclination was 45 degrees, as at Eglin. The Hen House radars scanned electronically, but were not phased arrays. Often likened to the BMEWS AN/FPS-50, the Hen House radars leapt forward in their surveillance range, from about 340 miles to 3,700 miles (3,200 nautical miles). The BMEWS radars of the early 1960s were more advanced in their UHF frequency range (400 MHz), but tracked only to an approximate distance of 2,000 miles. The Soviet Union built the first Hen House at Sary Shagan in the middle 1950s (Blake 1995; Bussert 1987, 117).

Interpretations vary regarding the timing of the sequential construction for Hen House, but analysts agree that at least several more of the system's radars were in place by the middle 1960s: at Mishelevka (vicinity of Irkutsk), facing China and the Pacific, and at Skrunda (Latvia), facing known American ICBM and SLBM launch paths. In 1969, construction began for the fourth Hen House site at Olenegorsh on the Kola peninsula, with a second radar added at Skrunda. The Soviets built fifth and sixth Hen House complexes at the outset of the 1970s, at Genichesk near the Black Sea and at Pinsk. Most of the locations had two radars each at final build-out, with 11 total radars at the six sites. The double-array configuration expanded the azimuth coverage sector. The size of the Hen House radars forbad any real hardening against nuclear attack, and in that respect the radars were quite different from the first ABM large phased-array radars built by the American military. The VHF band also made them particularly vulnerable to the effects of nuclear blackout. Analysts construed that Soviet engineers achieved the extremely long range of Hen House at a sacrifice in image resolution. The Soviet Union also built a battle-management radar to accompany the network. This radar is completely unlike those undertaken by the United States. Nicknamed the Dog House radar, it is an A-frame phased-array radar, having an open triangular shape. Also of extremely large size, Dog House may have been EMP hardened but was not hardened for nuclear blast. This radar operated in the VHF range of 100 MHz. Dog House received hand-off information from Hen House, and had a range of about 1,500 miles. In the 1970s, the Soviets added the Cat House battle-management radar, also phased-array. Both the Dog House (Kubinka, Moscow province) and Cat House (Stremilovo, Moscow province) radars were upgrades to the existing ABM network surrounding the capital of the Soviet Union, allowed under the ABM Treaty of 1972 (Zaloga 1989, 125-127, 133, 148; Bussert 1987, 118).

In the late 1970s and early 1980s, the Soviets began planning and construction of the next generation of the long-range surveillance radars, paralleling the development of the American

PAVE PAWS. The ABM Treaty restricted certain physical siting options for the continued deployment of Hen House or for a backup network at new locations. In addition, the permafrost conditions at several northern sites made it impossible to build Hen House radars at these desired sites. As a result, there remained gaps in physical coverage through the Hen House network. In 1978, the Soviets undertook construction of its first PAVE PAWS-like radar at Pechora. Analysts most often reference this radar as the key component of Hen Roost. The Hen Roost radar is designed as a bi-static system that has two distinct structures, one for transmitting and one for receiving. The design is closest to that for the AN/FPS-85 large, phased-array radar at Eglin of 1962-1969, and may indicate a Soviet lag behind the United States in large phased-array technology. A bi-static phased-array radar requires less sophisticated radar systems and accompanying computer control.

The transmitter and receiver buildings for Hen Roost are each very large, and of interesting comparison to PAVE PAWS. The receiver structure stands about 30 stories high, with a footprint approximately 295' square, while the transmitter structure stands about 11 stories high, and is approximately 492' long by 295' deep. Each structure sits on a raised rectangular base, and is in the shape of a truncated pyramidal square/rectangle. The literature describes Hen Roost radars as having a 20-degree inclined radar face, but Department of Defense published drawings of the system illustrate a receiver building with a 20-degree setback and a transmitter building with a deeper setback. Each installation features a side-by-side configuration for receiver and transmitter, with azimuth coverage mapped as between 60 and 120 degrees, varying by site. It is unclear as to whether the Hen Roost radars are steel-frame, metal-paneled in type, or reinforced concrete. Following an American visit to one of these radars in 1987, published indications are for a concrete shell of some kind, of poor construction, with windows. Independent power plants do not accompany the facilities. Analysts estimate that the Hen Roost system cost $300 to $400 million, per radar. Five sites were under construction during the early 1980s: at Pechora; Lyaki (near Iran); Mishelevka (near Irkutsk); Sary Shagan (Kazakhstan); and Karlovka (near Murmansk on the Barents Sea). Three of these locations provided direct redundancy with the pre-existing Hen House network (Zaloga 1989, 126-127, 142-144; 47-54, 329).

With the beginnings of construction of the large phased-array radar near Krasnoyarsk in 1983, the Soviets had expanded the Hen Roost network to six radars, with four more under construction by 1988. The 10 radars comprising the total system are located at Pechora, Lyaki, Mishelevka, Sary Shagan, Karlovka, Abalakovo, Mukhachevo, Baranovichi, Skrunda, and Sevastapol, built in this order between 1978 and the early 1990s. The radars followed the design of the first radar at Pechora, but from Krasnoyarsk forward featured a number of technical differences. The Krasnoyarsk controversy in the United States peaked in 1987, when both the Senate (93 to 2) and the House of Representatives (417 to 0) voted that this radar was a violation of the ABM Treaty. In September of that year, the Soviet Union allowed an American diplomatic group to visit the radar, which was still not completed, nor operational. Analysts generally argue that American large phased-array radars are technically superior to the Hen Roost network. However, in the Department of Defense publication *Soviet Military Power 1986*, the official argument favored Hen Roost over PAVE PAWS, making direct comparison. Final discussion centered on whether technical superiority mattered in military terms: possibly cruder equipment might be as effective as that with more sophisticated computer control, with EMP hardness arguments also varied. Today, the number of active Hen Roost radars is not readily available, but is assumed to be eight or less. The radar at Skrunda in Latvia was set for dismantling after 1996, with a $6 million contract awarded to an American company in October 1994 (Parrott 1987, 48-54, 68, 329; Blake 1995, 53-54).

In September 1998, the *New York Times* described the Skrunda radar as "closed" and the Soviet large phased-array radar system as "frayed." That same month Russian and American Presidents Yeltsin and Clinton signed an accord on ICBM and SLBM launches, offering American support to Russia. The *Times* further commented that "some [Soviet] ground-based radars are in poor repair. Others ended up on the wrong side of the border after the Soviet Union collapsed." The hope then was for a joint early warning system operational by 2000. Air Force Space Command planned to transmit information not only to the American command centers, but also directly to a Russian post such as the Center for Space and Military Situations near Moscow. The two nations' leaders hoped to monitor "the spread of missile technology in the third world" (Gordon 1998). The American government was also offering to assist Russia in completing "a large missile tracking radar" near Irkutsk. Not further identified, this radar may be the Hen Roost radar at Mishelevka from the early 1980s, either upgraded or in disrepair (Gordon 1999).

In addition to the Hen Roost expansion after 1983, the Soviet Union also built a huge battle-management radar as a part of an upgrading of its permitted ABM system around Moscow. This radar, named the Pill Box or Pushkino radar by the West, is a supplement or partial replacement of the Dog and Cat House battle-management radars. Built near Pushkino in the vicinity of Moscow, the radar is very large, with a footprint of about 500 feet on a side, and a height of 120 feet. In the shape of a truncated pyramid, the radar infrastructure is of reinforced concrete, with four active radar faces. The radar has 360-degree azimuth coverage. Construction occurred in the late 1980s, simultaneously with Soviet and American efforts toward rail-mobile ICBMs. Pill Box achieved operational status by the turn of the decade (Zaloga 1987, 140-141; Blake 1995, 13).

IX. ACRONYMS, RADAR NOMENCLATURE, AND SOURCES

Acronyms

ABM	-	antiballistic missile [defense system; treaty]
AFB	-	Air Force Base
ARPA	-	Advanced Research Projects Agency
AT&T	-	American Telegraph and Telephone
BMD	-	ballistic missile defense
BMEWS	-	Ballistic Missile Early Warning System
CDC	-	Control Data Corporation
DEW	-	Distant Early Warning [Line]
EMP	-	electromagnetic pulse
ENIAC	-	Electronic Numerical Integrator and Calculator
HABS	-	Historic American Buildings Survey
HAER	-	Historic American Engineering Record
HF	-	high frequency
IBM	-	International Business Machines
ICBM	-	intercontinental ballistic missile
IEEE	-	Institute of Electrical and Electronics Engineers
kV	-	kilovolt

kW	-	kilowatt
MHz	-	megahertz
MILSTAR	-	Military Strategic Tactical and Relay satellite system
NDRC	-	National Defense Research Council
NAVSPASUR	-	Naval Space Surveillance System
NHPA	-	National Historic Preservation Act
NORAD	-	North American Air Defense Command
NRHP	-	National Register of Historic Places
PA	-	Programmatic Agreement
PAVE PAWS	-	Perimeter Acquisition Vehicle Entry Phased-Array Warning System
RADC	-	Rome Air Development Center
RAM	-	random access core memory
RV	-	reentry vehicle
SAGE	-	Semi-Automatic Ground Environment
SATCOM	-	Satellite Communications
SDI	-	Strategic Defense Initiative
SHPO	-	State Historic Preservation Officer
SLBM	-	sea-launched ballistic missile
SPARS	-	undetermined
UHF	-	ultra high frequency
USACERL	-	United States Army Construction and Engineering Research Laboratory
USGS	-	United States Geological Survey
UTM	-	Universal Transverse Mercator
VHF	-	very high frequency
WACS	-	White Alice Communications System

Radar Nomenclature

American military electronic detection and tracking systems each have a special three-letter nomenclature that references installation, equipment, and purpose, as well as an assigned number. The two letters prefacing all radars, "AN," are a joint military-service designation historically derived from "Army" and "Navy" (Gross, Hall and Barton 1974, 6). The electronic equipment designations discussed herein are AN/CPS, AN/FPS, and AN/FSQ. For these terms:

CPS signified an air-transportable (C) radar (P) used for detection, range, and/or bearing (S);
FPS signifies a fixed (F) radar (P) used for detection, range, and/or bearing (S); and,
FSQ signifies a fixed (F) piece of special equipment (S) used for special purposes (Q).

Sources

Sources provided serve as references cited in this document. All drawings relevant to the discussion are listed, although do not have an item by item citation in the text. Organization is by material type.

Books, Journals, Printed Materials, and Web Sites

Allen, J.L. 1962. Array radars. A survey of their potential and their limitations. *The Microwave Journal* 5:67-79.

Amitay, Noack, Victor Galindo, and Chen Pang Wu. 1972. *Theory and analysis of phased array antennas*. New York: Wiley-Interscience.

Astrahan, Morton M. and John F. Jacobs. 1983. History of the design of the SAGE computer—the AN/FSQ-7. *Annals of the History of Computing* 5:340-349.

Aviation Week and Space Technology. 1980. U.S. upgrading ground-based sensors. *Aviation Week and Space Technology*. 112:239-242.

_____. 1983. Filter center. *Aviation Week and Space Technology*. 119:155.

Barton, David K. 1983. A half century of radar. *IEEE Transactions on Microwave Theory and Techniques*. MTT-32:1161-1169.

Blake, Bernard (ed). 1995. *Jane's radar and electronic warfare systems.* Seventh Edition. Coulsdon, Surrey: Jane's Information Group Limited and Alexandria, Virginia: Jane's Information Group Inc.

Brookner, Eli. 1977. *Radar technology.* Boston and London: Artech House.

_____. 1984 (May 15-17). Radar of the '80s and beyond. Paper presented to the IEEE in Session 4.

_____. 1985. Phased-array radars. *Scientific American*. 252:94-102.

_____. 1988a. Large phased-array Radars. In Dietrich Schroeer and David Hafemeister (eds), *Nuclear Arms Technologies in the 1990s*. American Institute of Physics Conference Proceedings 178. New York: American Institute of Physics, 165-205.

_____. 1988b. *Aspects of modern radar*. Boston and London, Artech House:

_____. 1991. *Practical phased-array antenna systems*. Boston and London, Artech House.

_____. 1997 (February 12-13). Current status of phased-array radars. Paper presented at the Third Radar/Electronic Warfare Conference at the Applied Physics Laboratory of Johns Hopkins University.

_____. 2000a (July 19). BMEWS and BMEWS upgrades. Typescript.

_____. 2000b (July 19). Early warning radar designations. Typescript.

Bruce-Briggs, B. 1988. *The shield of faith: a chronicle of strategic defense from zeppelins to Star Wars*. New York: Simon and Schuster, Inc.

Bussert, Jim. 1987. Whose phased-array radars violate the ABM Treaty? *Defense Electronics*. 19:116-124.

Carter, Ashton B. and David N. Schwartz (eds). 1983. *Ballistic missile defense*. Washington, D.C.: The Brookings Institution.

Ceruzzi, Paul. 1989. Electronics technology and computer science, 1940-1975: a coevolution. *Annals of the History of Computing*. 10:257-275.

Cole, Henry W. 1992. *Understanding radar*. Second edition. Cambridge, Massachusetts: Blackwell Scientific Publications.

Constant, James. 1972. *Defense radar systems engineering*. New York and Washington: Spartan Books.

Dashefsky, Edward L., and Palmer Derby. 1976. Martin Schilling. *Electronic Progress* 18:7-12.

Defense Electronics. 1985. Critical program reviews: strategic warning. *Defense Electronics*. 17:100-103.

Durch, William J. 1987. *The ABM Treaty and western security*. Cambridge, Massachusetts: Ballinger Publishing Company.

Fairbanks Daily News-Miner. 2001 (February). Clear Air Force Station pulls plug on 'dinosaur.' *Fairbanks Daily News-Miner*.

Gaffney, Frank. 1987. The strategic context of SDI: a US assessment of Soviet attitudes towards mutual vulnerability. Paper 19. In Bhupendra Jasani (ed), *Space weapons and international security*. New York: Oxford University Press, 281-296.

Gordon, Michael R. 1998 (September 2). U.S. to use its missile warning system to alert Russians to launchings worldwide. *New York Times*.

_____. 1999 (October 17). Asks Russia to alter treaty on missile defense. *New York Times*.

Gross, F.A., W.M. Hall, and D.K. Barton. 1974. Detection and tracking systems: an historical overview. *Electronic Progress*. 16:2-11.

Jacobs, John F. 1983. SAGE overview. *Annals of the History of Computing*. 5:323-329.

Jasani, Bhupendra (ed). 1987. *Space weapons and international security*. New York: Oxford University Press.

Jockel, J.T. 1987. *Boundaries upstairs: Canada, the United States, and the origins of North American air defence, 1945-1958*. Vancouver: University of British Columbia Press.

Johnson, Charles M. 1970. Ballistic-missile defense radars. *IEEE Spectrum*. 7:32-41.

Judge, John F. 1985. Strategic missile warning systems being upgraded. *Defense Electronics*. 17:86-92.

Laighton, D.G. 1988. Hybrid and monolithic microwave integrated circuitry. In Eli Brookner (ed), *Aspects of Modern Radar*. Boston and London: Artech House, 279-296.

MacKenzie, Donald. 1991. The influence of the Los Alamos and Livermore National Laboratories on the development of supercomputing. *Annals of the History of Computing*. 13:179-201.

Mayfield, Jerry. 1980. Air Force upgrading radar network. *Aviation Week and Space Technology*. 112:229-232.

Murray, Charles J. 1997. *The supermen: the story of Seymour Cray and the technical wizards behind the supercomputer*. New York: John Wiley & Sons, Inc.

Painter, Floyd C. 1987. Raytheon: profitable and growing. *Defense Electronics*. 20:67-78.

Parrott, Bruce. 1987. *The Soviet Union and ballistic missile defense*. Papers, School of Advanced International Studies, Johns Hopkins University. Boulder and London: Westview Press.

Raytheon. 1976. *Electronic Progress*. 18:30.

Rhinelander, John B. 1987. Implications of US and Soviet BMD programs for the ABM Treaty, Paper 8. In Bhupendra Jasani (ed), *Space weapons and international security*. New York: Oxford University Press, 145-161.

Sanger, David E. 2001 (December 15). Washington's new freedom, and new worries, in the post-ABM-Treaty era. *New York Times*.

Sanger, David E. and Michael Wines. 2002 (June 14). With a shrug, a monument to Cold War fades away. *New York Times*.

Schneiter, George. 1984. The ABM Treaty today. In Ashton B. Carter and David N. Schwartz (eds), *Ballistic missile defense*. Washington, D.C.: The Brookings Institution, 221-250.

Skolnik, Merrill I. 1962. *Introduction to radar systems*. New York: McGraw-Hill Book Company.

_____. 1985. Fifty years of radar. *Proceedings of the IEEE*. 73:182-197.

_____. 1990. *Radar handbook*. Second edition. New York: McGraw-Hill Publishing Company.

Space Policy Project. 1999. Military space programs. Information posted in 1999 at www.fas.org/spp/military/program/track/bmews.

Stark, Louis. 1974. Microwave theory of phased-array antennas—a review. *Proceedings of the IEEE*. 62:1661-1703.

Stein, Kenneth J. 1979. Pave Paws phased array radar nears acceptance. *Aviation Week and Space Technology*. 110:60-65.

_____. 1984. BMEWS update program progresses at Thule site. *Aviation Week and Space Technology*. 121:87, 91.

Thornton, James E. 1980. The CDC 6600 Project. *Annals of the History of Computing*. 2:338-348.

Valley, George E., Jr. 1985. How the SAGE development began. *Annals in the History of Computing*. 7:196-226.

White, Joseph F. 1984. Origins of high-power diode switching. *IEEE Transactions on Microwave Theory and Techniques*. MTT-32:1105-1117.

Zaloga, Steven J. 1989. *Soviet air defence missiles: design, development and tactics*. Surrey, U.K.: Jane's Information Group.

Government and Government-Sponsored Documents / Information

Control Data Corporation. 1969 (April 12 and December 12). *Advanced ballistic missile defense study*. Mid-Term and Final Reports. Minneapolis: CDC for the U.S. Army Nike-X Development Office.

Cross, Coy F. II. 1997. *From the Stone Age to the Space Age: a history of Beale AFB*. Washington, D.C.: U.S. Government Printing Office.

Del Papa, E. Michael and Mary P. Warner. 1991 (October). *Historical chronology of the Electronic Systems Division 1947-1990*. Hanscom Air Force Base: Electronic Systems Division History Office.

Hoffecker, John F. and Mandy Whorton. 1996 (September). *Historic properties of the Cold War era [under the management of] 21st Space Wing U.S. Air Force Space Command.* Draft. Lakewood, Colorado: Argonne National Laboratory.

Lonnquest, John C. and David F. Winkler. 1996 (November). *To defend and deter: the legacy of the United States Cold War missile program.* USACERL Special Report 97/01. Champaign, Illinois: USACERL.

National Research Council. 1979. *Radiation intensity of the PAVE PAWS radars system: a report by the engineering panel on the PAVE PAWS radar system of the assembly of engineering, National Research Council.* Washington, D.C.: National Academy of Sciences.

Raytheon Company. 1987 (January 16). *Proposal for PAVE PAWS Upgrade Program. Technical operations data.* Volume I. Wayland, Massachusetts: Raytheon for Air Force Systems Command.

_____. 1988 (April 20). *System performance specification for phased array warning system, PAVE PAWS AN/FPS-123 (V)1, (V)2, (V)3, (V)4.* Wayland, Massachusetts: Raytheon for Air Force Systems Command.

_____. 1990 (January 10). *Final plan installation and integration rev. B. PAVE PAWS site 1 and site 2 upgrade.* Wayland, Massachusetts: Raytheon for Air Force Systems Command.

Schaffel, Kenneth. 1991. *The emerging shield: the Air Force and the evolution of continental air defense 1945-1960.* Washington, D.C.: Office of Air Force History.

Singcaster, Capt. F., Headquarters Air Force Space Command. 1997. Captains in missile warning link. Information posted in 1998 at www.dnd.ca/commelec/vol32/part16.html.

Smith, John Q. and David A. Byrd. 1991. *Forty years of research and development at Griffiss Air Force Base.* Rome, New York: Air Force Research Center History Office.

Thompson, Thomas W. and Cassandra A. Scott. 1986. *RADC history highlights, 1951-1986.* Rome, New York: Air Force Research Center History Office.

United States Air Force. Air Force Materiel Command. Electronic Systems Center. 1997. Statement of objectives for the Clear radar upgrade. Information posted in 1998 at www.fas.org/spp/military/program/track/clear/soo4.htm. 28 March.

United States Air Force. Air Force Space Command. n.d. PAVE PAWS scrapbook. Held at the PAVE PAWS facility, Beale Air Force Base.

_____. 1997. "Guardians of the high frontier." Information posted in 1998 at www.spacecom.af.mil/HQAFSPC/library/brochure/page17/page17.htm.

United States Air Force. Air Force Space Command. 7th Missile Warning Squadron. 1990. *Welcome 7th Missile Warning Squadron.* Held at the History Office, Beale Air Force Base.

United States Air Force. Air Force Space Command. 9th Missile Warning Squadron. 1985 (July-December). *History of the 9th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

_____. 1986 (January-June). *History of 9th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

United States Air Force. Air Force Space Command. 10th Missile Warning Squadron. 1986 (October-December). *History of the 10th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

United States Air Force. Second Weather Squadron. 1978 (January-June). *History of the 2nd Weather Squadron. Supporting documentation*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

United States Air Force. Space Command. 1020th Computer Services Squadron. 1983 (May-June). *History of 1020th Computer Services Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

United States Air Force. Strategic Air Command. 100th Air Refueling Wing. 1977. *PAVE PAWS fact book*. Pamphlet held as "Item 11 – Historical Research & Reference. Photos – PAVE PAWS" at the History Office, Beale Air Force Base.

United States Air Force. Strategic Air Command. 7th Missile Warning Squadron. 1980a (December 1979 – March 1980). *History of 7th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

_____. 1980b (April-June). *History of 7th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

_____. 1980c (October-December). *History of 7th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

_____. 1981a (January-March). *History of 7th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

_____. 1981b (April-June). *History of 7th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

_____. 1981c (July-September). *History of 7th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

_____. 1981d (October-December). *History of 7th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

_____. 1982a (April-June). *History of 7th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

_____. 1982b (July-September). *History of 7th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

_____. 1982c (October-December). *History of 7th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

United States Air Force. Strategic Air Command. 6th Missile Warning Squadron. 1980a (April-June). *History of 6th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

_____. 1980b (July-September). *History of 6th Missile Warning Squadron*. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

_____. 1981 (April-June). *History of 6th Missile Warning Squadron*. April – June. Held at the Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, Alabama.

Weitze, Karen J. 1992 (August). *Re-evaluation of the NRHP eligibility for the White Alice installations at Bethel, Middleton Island & Pedro Dome, Alaska*. Austin, Texas: Dames & Moore, Inc. for the Stanford Research Institute.

_____. 1996 (October). *Travis Air Force Base Fairfield, California. Inventory of Cold War properties*. Plano, Texas: Geo-Marine, Inc. for Air Mobility Command.

_____. 1999 (February). *PAVE PAWS Beale Air Force Base: historic evaluation and context*. San Diego: KEA Environmental, Inc. for Air Combat Command.

White, Ronald K. 1980 (July). *Final Environmental Impact Statement. Operation of the PAVE PAWS radar system at Beale Air Force Base, California*. Menlo Park, California: Stanford Research Institute.

Whorton, Mandy. 2000 (August). *Deter and defend: the history of the development and operation of the PAVE PAWS radar network*. Lakewood, Colorado: Argonne National Laboratory for Air Force Space Command.

Winkler, David F. 1997 (June). *Searching the skies: the legacy of the United States Cold War defense radar program*. Champaign, Illinois: USACERL for Air Combat Command.

<u>Drawings, Maps and Photographs</u>

Black & Veatch. 1990 (February). *PAVE PAWS. Install exterior area lights*. Kansas City: Black & Veatch. Held at Civil Engineering, Beale Air Force Base.

Carissimi Rohrer Associates. 1986a. *PAVE PAWS boundary security system. Beale Air Force Base, California.* Sacramento: Carissimi Rohrer Associates. Held at Civil Engineering, Beale Air Force Base.

_____. 1986b (April). *PAVE PAWS boundary security system. Beale Air Force Base, California. Grading plans*. Sacramento: Carissimi Rohrer Associates. Held at Civil Engineering, Beale Air Force Base.

Idaho National Engineering Laboratory. 1990a (June). *PAVE PAWS Beale Air Force Base. Baseline documentation. Layout first levels and roof plans*. Idaho National Engineering Laboratory. Held at Civil Engineering, Beale Air Force Base.

_____. 1990b (June). *PAVE PAWS Beale Air Force Base. Baseline documentation. Site plan and area plan*. Idaho National Engineering Laboratory. Held at Civil Engineering, Beale Air Force Base.

_____. 1990c (June). *PAVE PAWS Beale Air Force Base. Baseline documentation. Utility plans*. Idaho National Engineering Laboratory. Held at Civil Engineering, Beale Air Force Base.

Koenigshofer Engineers. 1987a (July). *Beale Air Force Base. Supply warehouse (PAVE PAWS). Floor plan & schedules*. Sacramento: Koenigshofer Engineers. Held at Civil Engineering, Beale Air Force Base.

_____. 1987b (July). *Beale Air Force Base. supply warehouse (PAVE PAWS). Sections, elevations & refl. clng. Plan*. Sacramento: Koenigshofer Engineers. Held at Civil Engineering, Beale Air Force Base.

Markrist Company. 1984a (February). *PAVE PAWS power line. PAVE PAWS sub-station. Dead-end profile*. Orange, California: Markrist Company. Held at Civil Engineering, Beale Air Force Base.

_____. 1984b (February). *PAVE PAWS power line. PAVE PAWS substat'n dead-end. Struct'r elev. & det'ls*. Orange, California: Markrist Company. Held at Civil Engineering, Beale Air Force Base.

_____. 1984c (February). *PAVE PAWS power line. Project plot plan*. Orange, California: Markrist Company. Held at Civil Engineering, Beale Air Force Base.

_____. 1984d (February). *PAVE PAWS power line. Radar facility site plan*. Orange, California: Markrist Company. Held at Civil Engineering, Beale Air Force Base.

Raytheon and United Engineers & Construction. (with Tudor Braccia Bentley, San Francisco). 1977a (January). *PAVE PAWS technical facility Beale AFB. Site grading plan*. Boston: Raytheon. Held at the PAVE PAWS facility, Beale Air Force Base.

_____. 1977b (January). *PAVE PAWS technical facility Beale AFB. Site utility plan*. Boston: Raytheon. Held at the PAVE PAWS facility, Beale Air Force Base.

_____. 1977c (March). *SLBM-radar support facility. Phase I, Site improvements. Beale AFB, California. Site grading and drainage plan*. Boston: Raytheon. Held at Civil Engineering, Beale Air Force Base.

_____. 1977d (March). *SLBM-radar support facility. Phase I, Site improvements. Beale AFB, California. Project electrical 60kV distribution line plan*. Boston: Raytheon. Held at Civil Engineering, Beale Air Force Base.

_____. 1977e (March). *SLBM-radar support facility. Phase I, Site improvements. Beale AFB, California. 60kV distribution plan and profile*. Boston: Raytheon. Held at Civil Engineering, Beale Air Force Base.

_____. 1977f (March). *SLBM-radar support facility. Phase I, Site improvements. Beale AFB, California.60kV switching station and 60/2.4kV substation. Arrangement*. Boston: Raytheon. Held at Civil Engineering, Beale Air Force Base.

_____. 1977g (March). *SLBM-radar support facility. Phase I, site improvements. Beale AFB, California. 60kV switching station and 60/2.4kV substation. Plans*. Boston: Raytheon. Held at Civil Engineering, Beale Air Force Base.

_____. 1977h (September). *SLBM-radar support facility. Phase II. Beale AFB, California. Gate house. Plan, elev. & sections*. Boston: Raytheon. Held at Civil Engineering, Beale Air Force Base.

_____. 1977i (September). *SLBM-radar support facility. Phase II. Beale AFB, California. Guard tower. Plans, elevations & sections*. Boston: Raytheon. Held at Civil Engineering, Beale Air Force Base.

_____. 1977j (September). *SLBM-radar support facility. Phase II. Beale AFB, California. Power plant. Elevations & section*. Boston: Raytheon. Held at Civil Engineering, Beale Air Force Base.

_____. 1977k (September). *SLBM-radar support facility. Phase II. Beale AFB, California. Power plant. Floor plan*. Boston: Raytheon. Held at Civil Engineering, Beale Air Force Base.

_____. 1977l (September). *SLBM-radar support facility. Phase II. Beale AFB, California. Power plant. Floor plan cont*. Boston: Raytheon. Held at Civil Engineering, Beale Air Force Base.

Raytheon, United Engineers & Construction, and Jackson & Moreland International Inc. 1977 (January). *PAVE PAWS technical facility Beale AFB. First floor & platform 1A. Second floor & platform 2A. Third floor & platform 3A. Fourth floor & platform 4A*. Boston: Raytheon. Held at the PAVE PAWS facility, Beale Air Force Base.

_____. ca.1977/1985. *PAVE PAWS technical facility. Beale AFB. Equipment layout. First floor & platform 1A. Second floor & platform 2A. Fourth floor & platform 4A. Fifth floor & platform 5A*. Boston: Raytheon. Held at the PAVE PAWS facility, Beale Air Force Base.

Sverdrup & Parcel. 1985a. *PAVE PAWS facility. Beale Air Force Base. Power plant. Mechanical. floor plan. North end & corridor plan*. St. Louis: Sverdrup & Parcel. Held at Civil Engineering, Beale Air Force Base.

_____. 1985b. *PAVE PAWS facility. Beale Air Force Base. Support area. Architectural. Microwave equipment bldg. Microwave tower*. St. Louis: Sverdrup & Parcel. Held at Civil Engineering, Beale Air Force Base.

_____. 1985c. *PAVE PAWS facility. Beale Air Force Base. Technical facility. Architectural. Elevations A, B & C.* St. Louis: Sverdrup & Parcel. Held at Civil Engineering, Beale Air Force Base.

_____. 1985d. *PAVE PAWS facility. Beale Air Force Base. Technical facility. Architectural. Elevations D, E & F.* St. Louis: Sverdrup & Parcel. Held at Civil Engineering, Beale Air Force Base.

_____. 1985e. *PAVE PAWS facility. Beale Air Force Base. Technical facility. Architectural. equipment layout. First floor & platform 1A. Second floor & platform 2A. Third floor & platform 3A. Fourth floor & platform 4A. Fifth floor & platform 5A.* St Louis: Sverdrup & Parcel. Held at Civil Engineering, Beale Air Force Base.

_____. 1985f. *PAVE PAWS facility. Beale Air Force Base. Technical facility. Architectural. First floor & platform 1A. Second floor & platform 2A. Third floor & platform 3A. Fourth floor & platform 4A. Fifth floor & platform 5A.* St Louis: Sverdrup & Parcel. Held at Civil Engineering, Beale Air Force Base.

_____. 1985g. *PAVE PAWS facility. Beale Air Force Base. Technical facility. Architectural. Utility building. Plans & elevations*. St Louis: Sverdrup & Parcel. Held at Civil Engineering, Beale Air Force Base.

_____. 1985h. *PAVE PAWS facility. Beale Air Force Base. Technical facility. Structural. Utility building*. St Louis: Sverdrup & Parcel. Held at Civil Engineering, Beale Air Force Base.

United States Air Force, Strategic Air Command. 1980 (June). *Beale AFB, Calif. Relocate PAVE PAWS guard tower. Site plan and details*. Held at Civil Engineering, Beale Air Force Base.

_____. 1982a (March). *Beale Air Force Base, California. Satellite earth terminal. Phase I.* Held at Civil Engineering, Beale Air Force Base.

_____. 1982b (April). *Beale Air Force Base, California. Install PAVE PAWS computer. Layout & floor plan*. Held at Civil Engineering, Beale Air Force Base.

<u>Interviews</u>

Brookner, Eli. Raytheon. 2001 (March 9). Interview by Dr. Ruth Liebowitz and Dr. Karen J. Weitze. Tape recording held at Hanscom Air Force Base.

Burress, Chet. PAVE PAWS, Beale Air Force Base. 1998 (June 3 and 5). Discussions with Dr. Karen J. Weitze of Raytheon 16mm films for Cobra Dane and the Cape Cod PAVE PAWS.

Creek, Randy. PAVE PAWS, Beale Air Force Base. 1998 (June 3). Discussions with Dr. Karen J. Weitze, with a tour of the radar and computer equipment in Building 5760.

Emich, Lieutenant Colonel John. Air Force Space Command, PAVE PAWS, Beale Air Force Base. 1998 (June 3). Discussions with Dr. Karen J. Weitze and tour of Building 5760.

Hall, Frank. Raytheon site manager, PAVE PAWS, Beale Air Force Base. 1998 (June 5). Discussions with Dr. Karen J. Weitze.

Heath, Dave. Computer specialist, PAVE PAWS, Beale Air Force Base. 1998 (June 16). Telephone discussions with Dr. Karen J. Weitze. Site employee for 20 years. Originally with Control Data Corporation.

Wood, John. Power plant manager, PAVE PAWS, Beale Air Force Base. 1998 (June 3). Discussions with Dr. Karen J. Weitze and tour of the PAVE PAWS power plant (Building 5761).

X. PROJECT INFORMATION

During 1998 and 1999, Air Combat Command assessed the National Register of Historic Places (NRHP) significance of the PAVE PAWS radar at Beale Air Force Base in compliance with Sections 106 and 110 of the National Historic Preservation Act (NHPA). In consultation with the California Office of Historic Preservation, the Air Force decided that the Beale PAVE PAWS was eligible for the NRHP under criteria A and C at the national level of significance, supporting pre-existing informal Air Force judgments of 1994-1996. In conjunction with the NRHP evaluation, Air Combat Command also contracted for a historic context for the Beale PAVE PAWS. Dr. Karen J. Weitze of KEA Environmental, Inc. (now EDAW, Inc.), wrote a joint document for Air Combat Command, entitled *PAVE PAWS Beale Air Force Base: Historic Evaluation and Context* (February 1999).

While this process went forward during 1998, Air Force Space Command entered into a four-state Programmatic Agreement (PA) covering the PAVE PAWS in Massachusetts, California, Georgia, and Texas. Signators for the PA included the State Historic Preservation Officers (SHPOs) and representatives of the Air Force. The document was submitted to the Advisory Council on Historic Preservation. The PA referenced a prior agreement between the SHPOs and the Air Force to conduct a Level II Historic American Buildings Survey (HABS) / HAER documentation for the first PAVE PAWS at Cape Cod, with Level III HABS/HAER documentation at each of the other three radar installations. In addition, Air Force Space Command would contract for a system-wide historical context. Argonne National Laboratory managed the HABS/HAER documents process for the Cape Cod, Robins, and Eldorado PAVE PAWS, and submitted the history document in August 2000. Mandy Whorton of Argonne wrote this contextual history, entitled *Deter and Defend: The History of the Development and Operation of the PAVE PAWS Radar Network.* The two existing histories, those of Dr. Weitze and Ms. Whorton, complement each other. The earlier history (Weitze) looks at the larger context of phased-array radar, while the later one (Whorton) provides an overview history of the four PAVE PAWS radars.

To complete the PA requirements, Air Combat Command next contracted with KEA (now EDAW) to have Dr. Weitze use her historic context of 1999 as the basis for a HAER documentation of the PAVE PAWS at Beale. At Beale, Air Force Space Command operates the PAVE PAWS as a tenant on base, with Air Combat Command the installation host. Air Combat Command is responsible for environmental compliance, inclusive of cultural resource management. For the Beale PAVE PAWS HAER, Air Combat Command requested that an oral interview with international radar expert Dr. Eli Brookner of Raytheon be a part of the document. To complete this process, Dr. Weitze worked with Dr. Ruth Liebowitz, the historian for the Electronic Systems Center at Hanscom Air Force Base in Boston. The interview of March 2001 is segregated from the HAER, and is held as a tape recording at Hanscom. In addition, a synopsis of the interview is filed in the field notes for the HAER. The HAER herein submitted is more comprehensive than a typical Level III document, incorporating information from the existing context of 1999 and expanding discussion of the physical working apparatus of the radar.

A team of individuals collaborated on the Beale PAVE PAWS HAER.

Karen J. Weitze:	Dr. Weitze is an historian of military architecture and engineering. At the time of the initial project, Dr. Weitze worked for KEA Environmental, Inc., in San Diego, California (now subsumed within EDAW, Inc.). In 2001, Dr. Weitze became the owner of Weitze Research. Dr. Weitze conducted the research and analysis for the HAER, and is responsible for the draft and final written documentation.
Joseph Murphey:	Mr. Murphey is an architect and large-format photographer at the Fort Worth District, United States Army Corps of Engineers. He photographed the Beale PAVE PAWS during September 2000 and July 2005.
Robert A. Hicks:	Mr. Hicks is a large-format photographer and owner of Robert Hicks Photo in Rancho Cordova, California. Mr. Hicks photographed several Beale PAVE PAWS buildings in March 2006.
Kristin Kaiser:	Ms. Kaiser of KEA, Inc. (now EDAW) assisted Dr. Weitze and Dr. Liebowitz in their preparations for the oral interview at Hanscom Air Force Base with Dr. Eli Brookner during March 2001.
Christy Dolan:	Ms. Dolan of KEA, Inc. (now EDAW) assisted Dr. Weitze in the compilation of the draft document, inclusive of the labeling of the archival photographs and negatives. Ms. Dolan oversaw the formatting and graphics for the draft HAER.
Geo-Marine, Inc.:	Personnel at Geo-Marine, Inc., Plano, Texas, handled oversight of the final HAER in 2006.